Future Prospects of Hadron Physics at J-PARC
& Large Scale Computational Physics

Ibaraki Quantum Beam Research Center
February 12, 2013

Nucleon structure at Jefferson Lab (and J-PARC)

Wally Melnitchouk

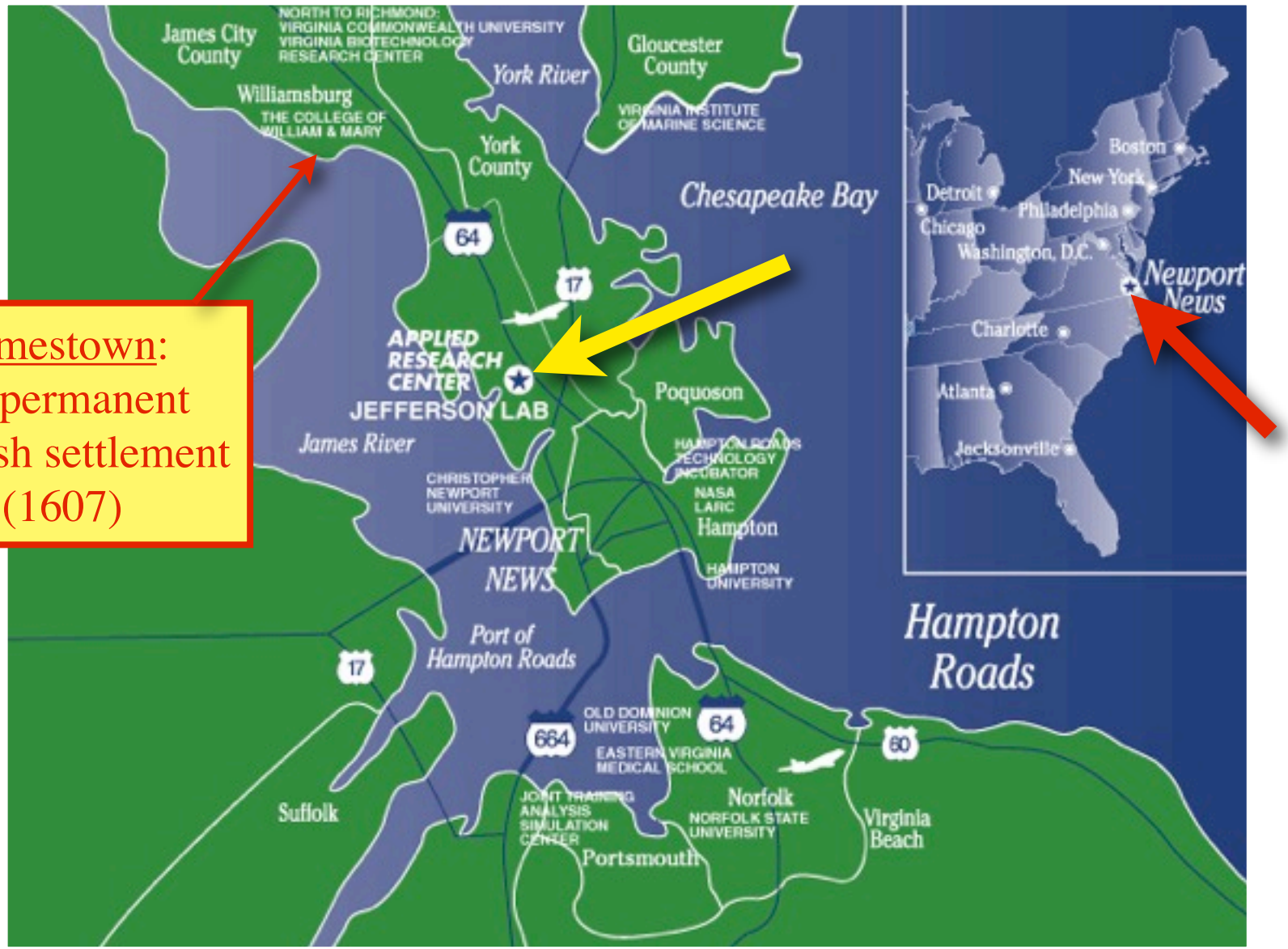
Jefferson Lab

Outline

- Brief tour of Jefferson Lab
- Longitudinal nucleon structure
  - → unpolarized and helicity distributions
- Transverse nucleon structure
  - → TMDs and GPDs
- Outlook
  - → 12 GeV upgrade
  - → Electron Ion Collider

Jefferson Lab Overview

Thomas Jefferson National Accelerator Facility (Jefferson Lab)



Jamestown:
1st permanent
English settlement
(1607)

located in Newport News, Virginia

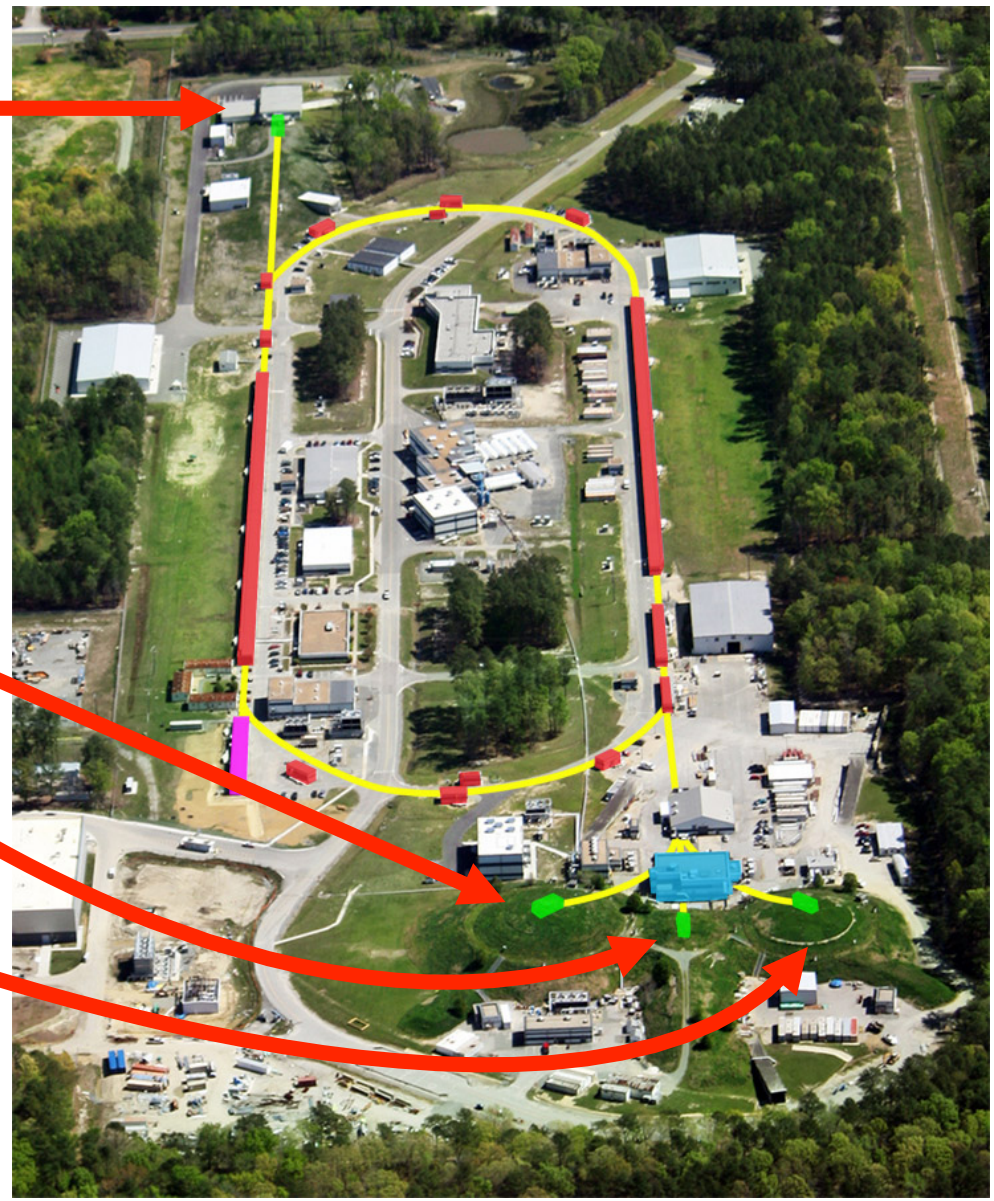
CEBAF at Jefferson Lab

HALL D

HALL A

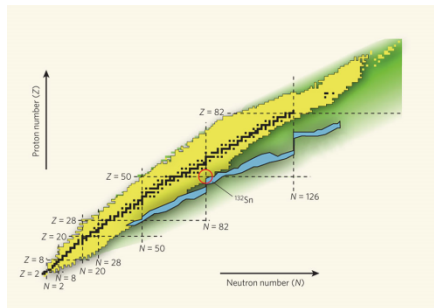
HALL B

HALL C

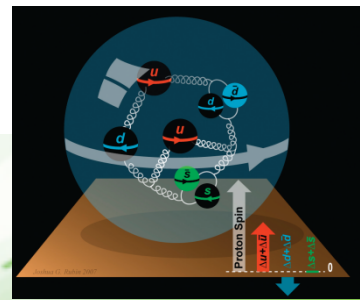


Continuous
Electron
Beam
Accelerator
Facility

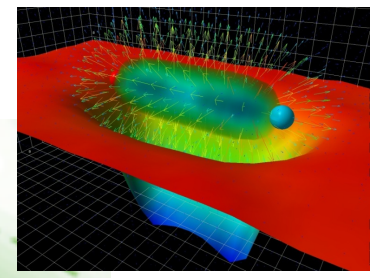
A Laboratory for Nuclear Science



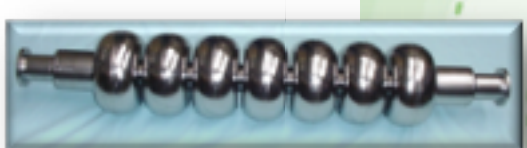
Nuclear structure



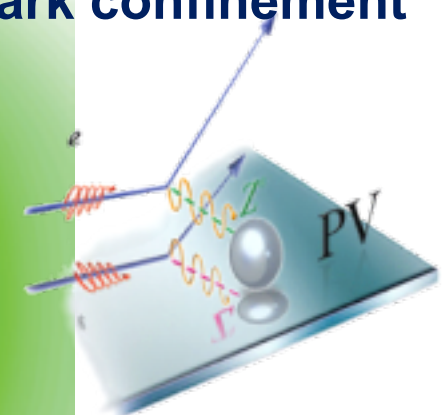
Hadron structure



Quark confinement

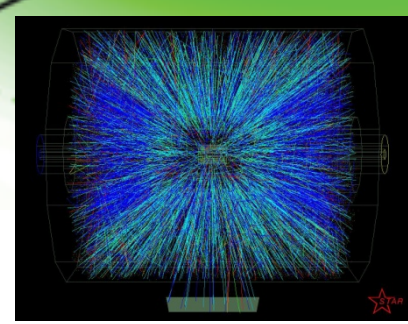


Accelerator S&T



Fundamental symmetries

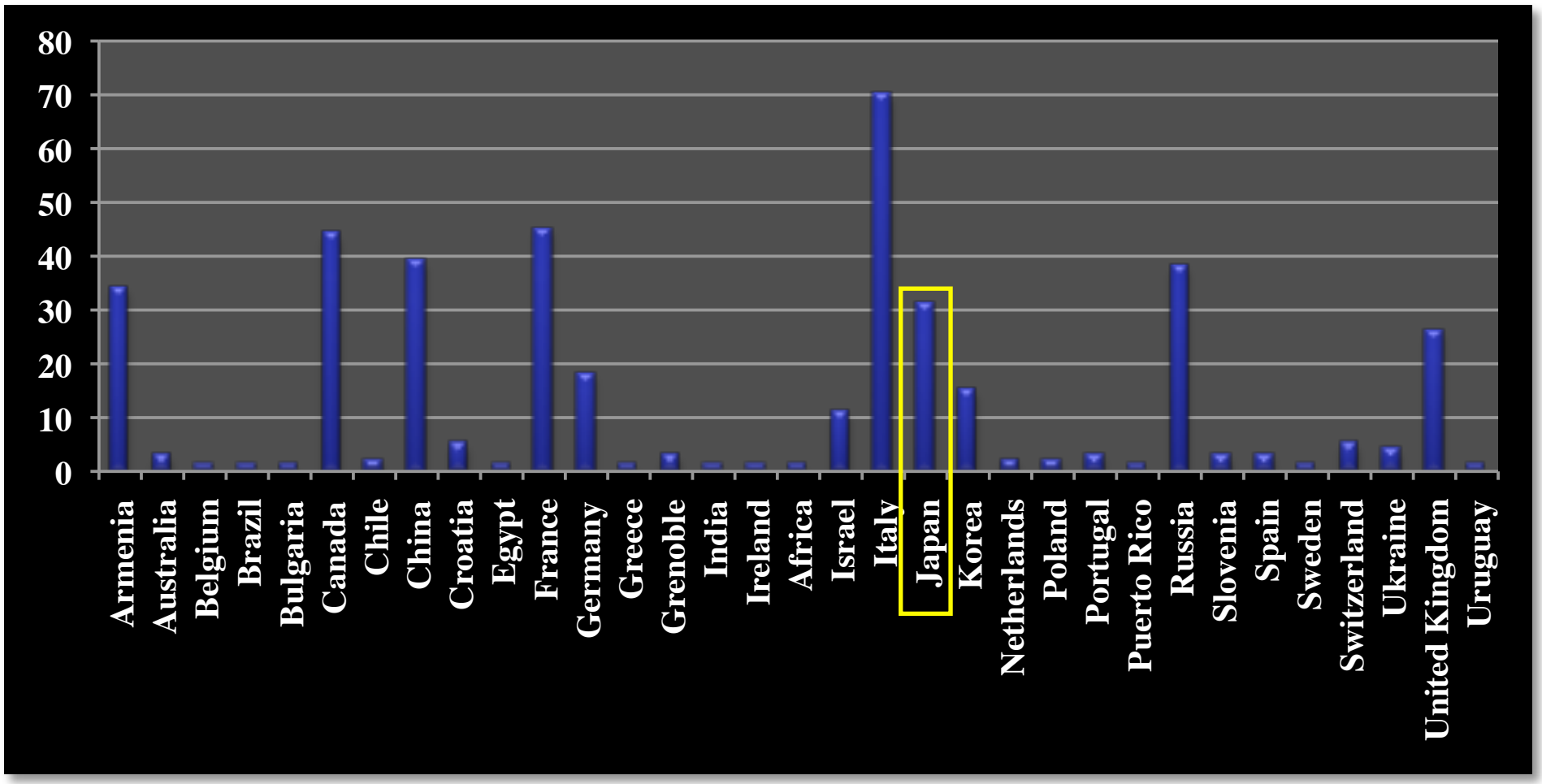
Medical imaging



Hadrons from quarks

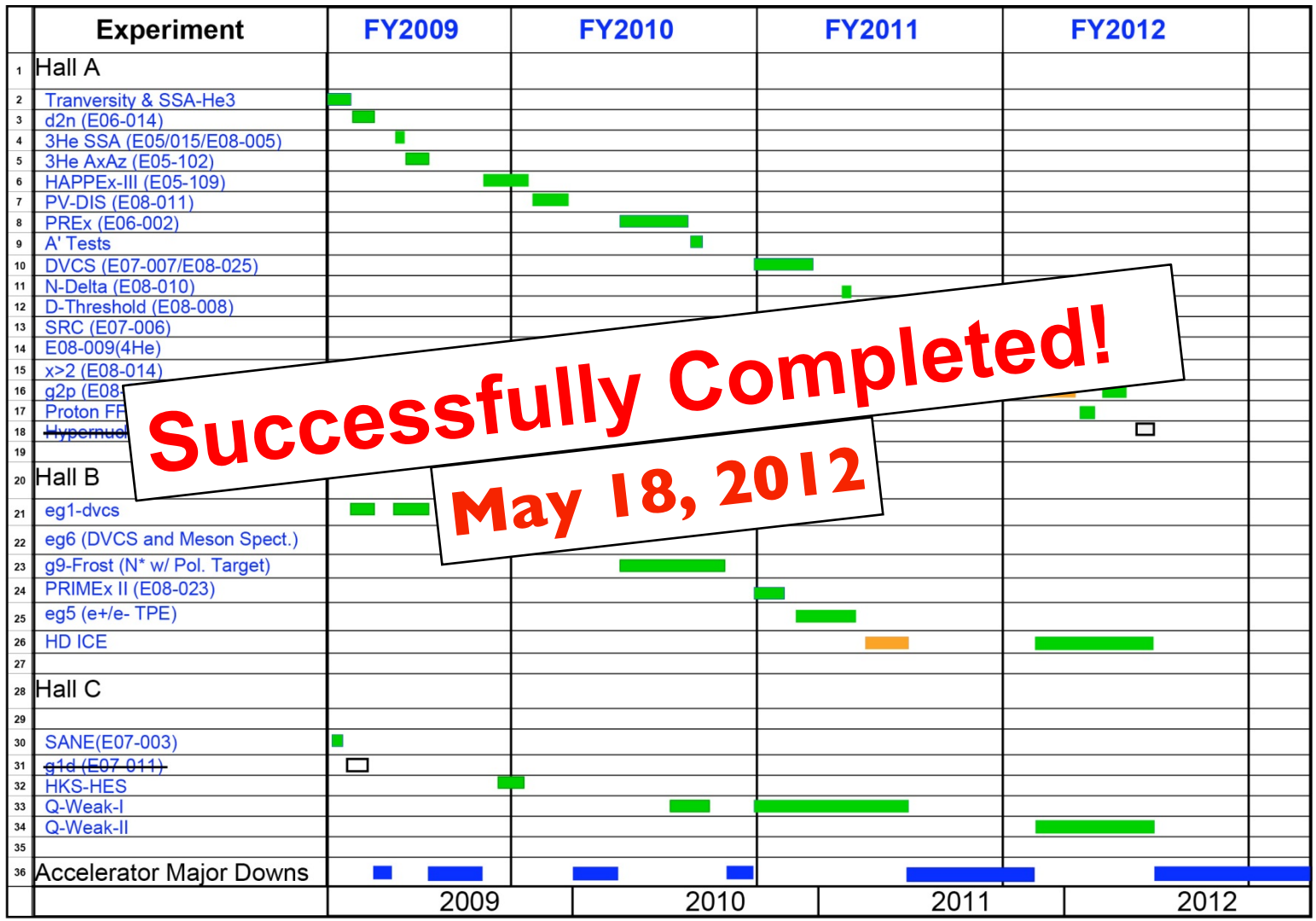
Theory & computation

A Laboratory for Nuclear Science



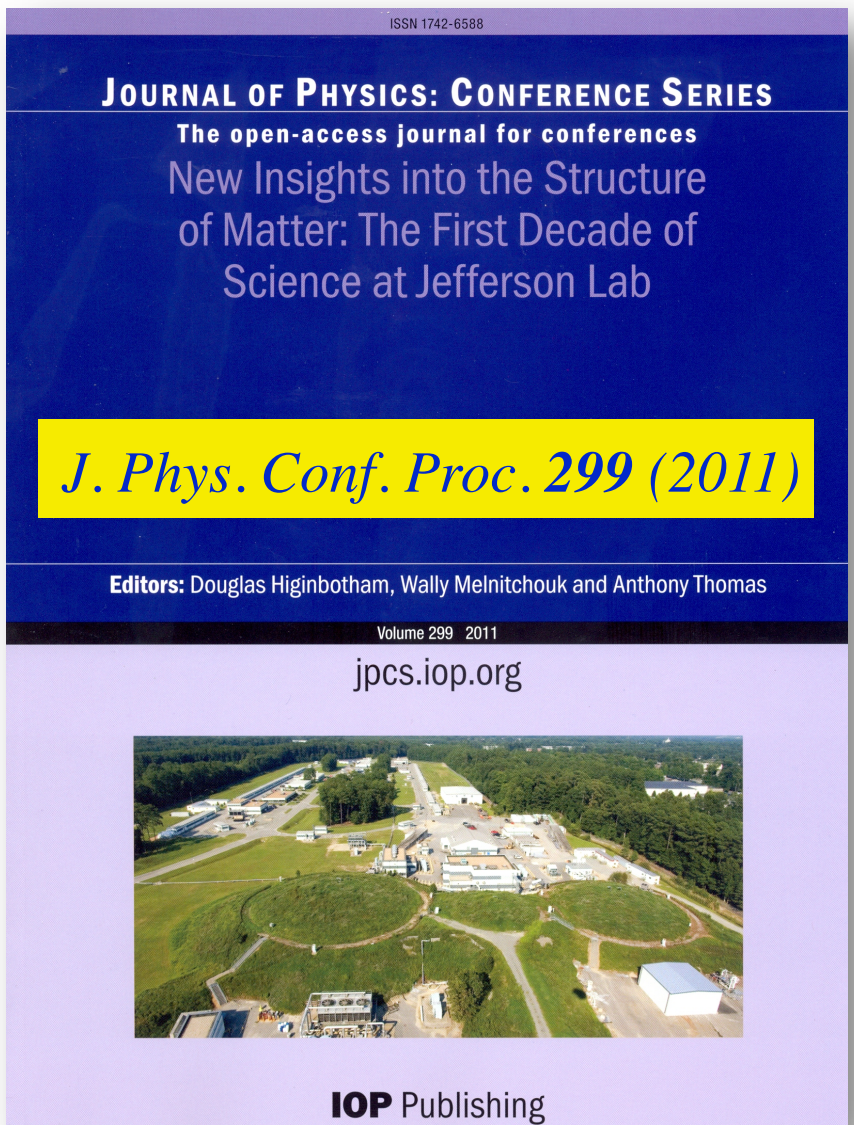
- ~ 1400 users (2/3 US, 1/3 foreign)
- ~ 1/3 of all US PhDs in nuclear physics

6 GeV Experimental Nuclear Physics Program



6 GeV Experimental Nuclear Physics Program

"The First Decade of Science at Jefferson Lab"



Foreword: A Long Decade of Physics

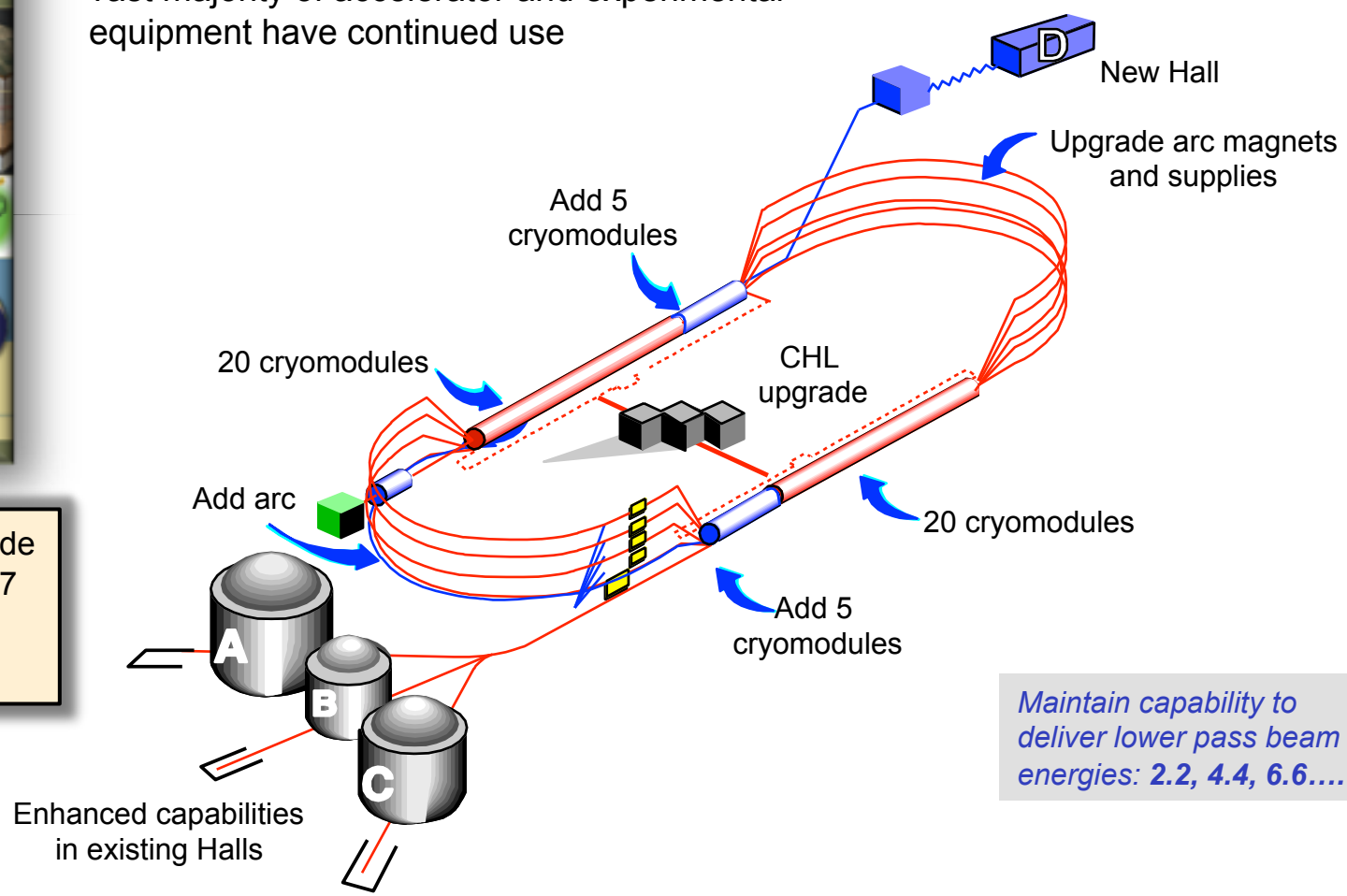
- Making the case for Jefferson Lab
- Nucleon Form Factors
- Strange Vector Form Factors
- Unpolarized Structure Functions
- Spin Structure Functions
- Deeply Virtual Exclusive Processes
- Lattice QCD
- Results from the N* Program
- Transition to Perturbative QCD
- Short-Distance Structure of Nuclei
- Medium Modifications of Hadrons & Partons
- Searches for Physics Beyond the SM
- Hypernuclear Spectroscopy
- The Free Electron Laser Program
- CEBAF Accelerator Achievements

12 GeV Upgrade of CEBAF

- Double accelerator energy 6 → 12 GeV
- New experimental Hall D, and upgrades to existing Halls

Completion of 12 GeV Upgrade ranked highest priority in 2007 NSAC Long Range Plan (reaffirmed in Jan. 2013)

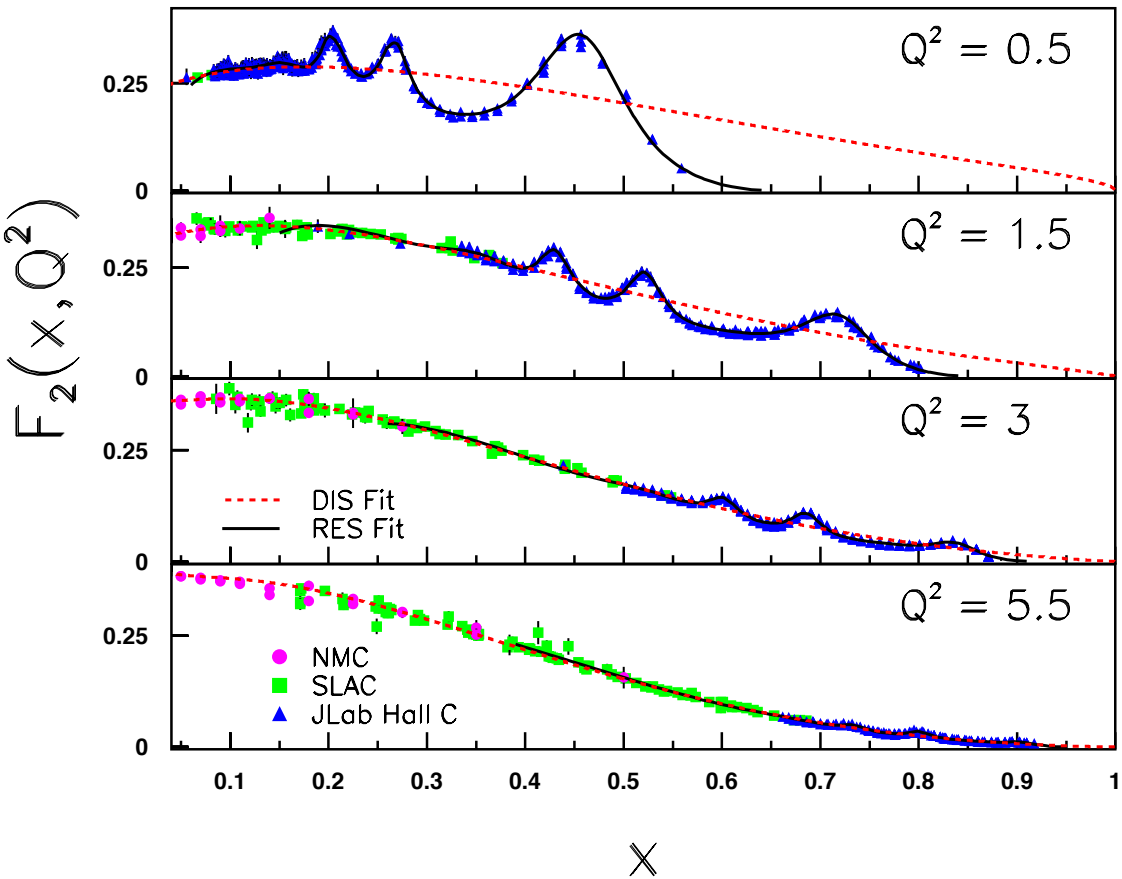
Upgrade designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use



Maintain capability to deliver lower pass beam energies: ***2.2, 4.4, 6.6….***

Longitudinal Nucleon Structure

Inclusive DIS structure functions



Christy, WM
*JPCS **299**, 012004 (2011)*

- Detailed mapping of resonance−scaling transition region

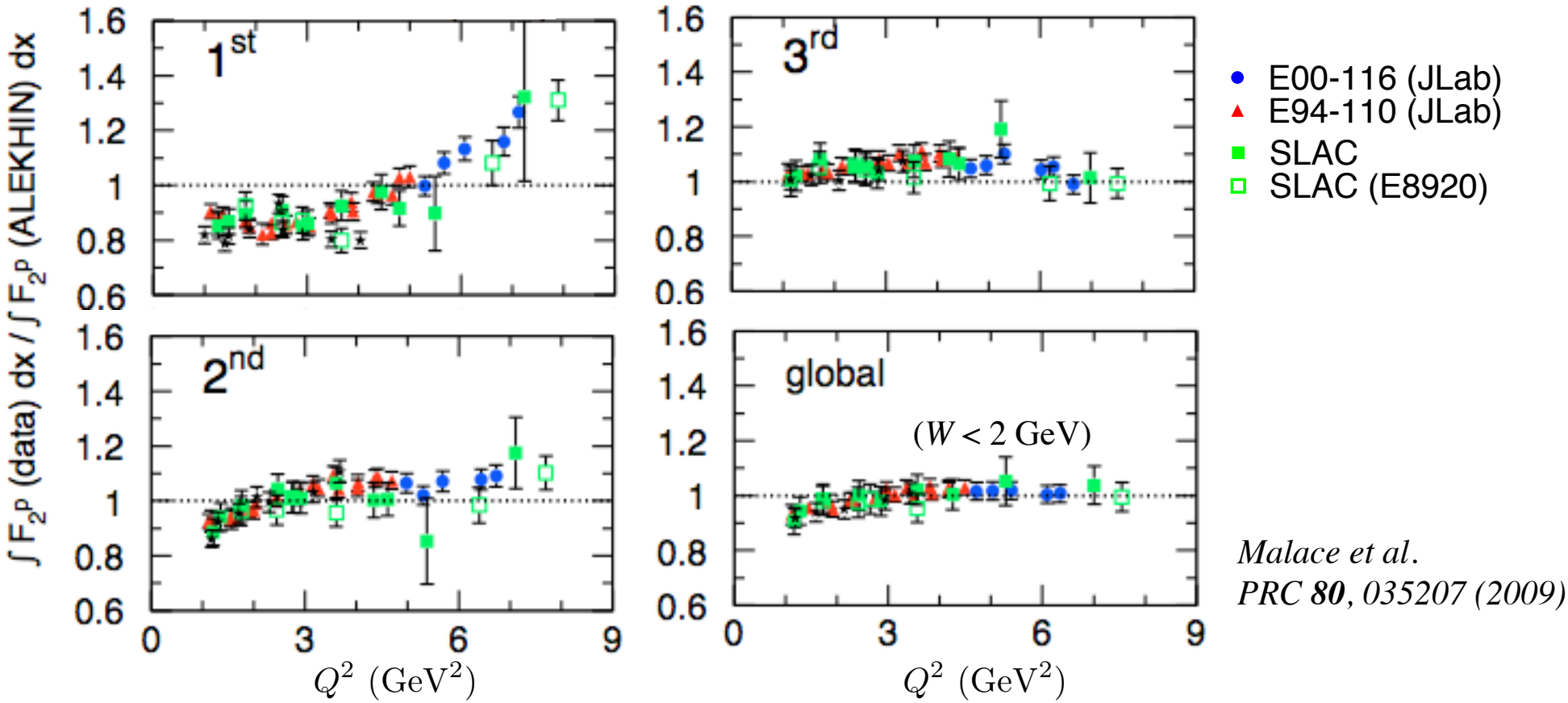
→ high precision tests of quark-hadron duality

square of sum ⟷ sum of squares

"coherent" "incoherent"

WM, Ent, Keppel
*PRep. **406**, 127 (2005)*

Inclusive DIS structure functions



Malace et al.
PRC ***80****, 035207 (2009)*

- Comparison of low- and high-W data shows remarkable *duality* between resonance and partonic descriptions

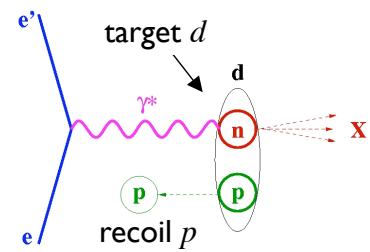
  → strong cancellation of higher twists

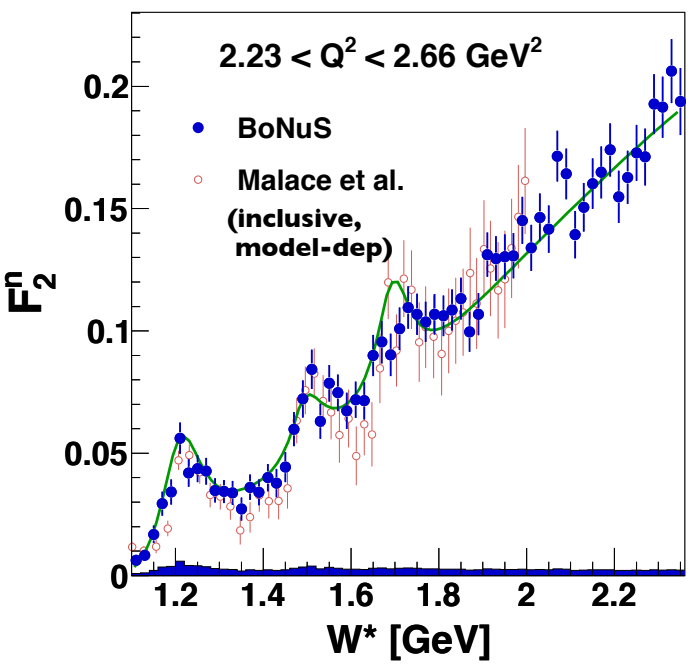
  $\lesssim 10\text{–}15\%$ for $Q^2 > 1\text{GeV}^2$

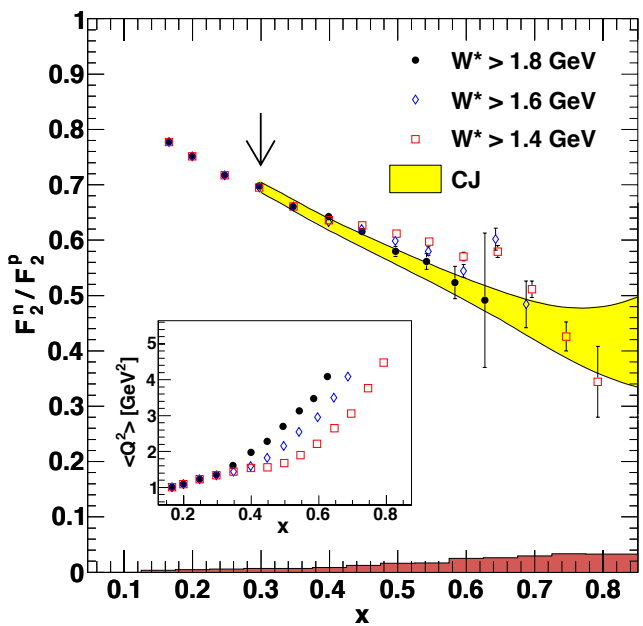
Inclusive DIS structure functions

- Confirmation requires (free) *neutron* data

→ BoNuS experiment (tag slow, backward proton in SIDIS from deuteron)





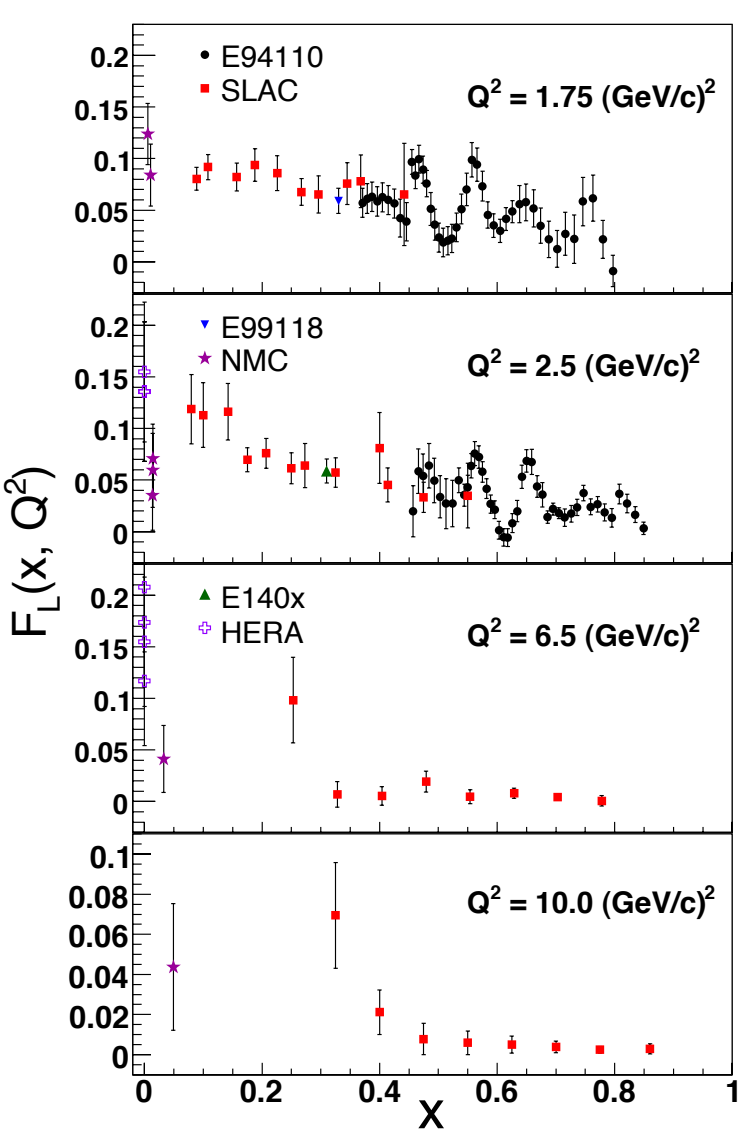


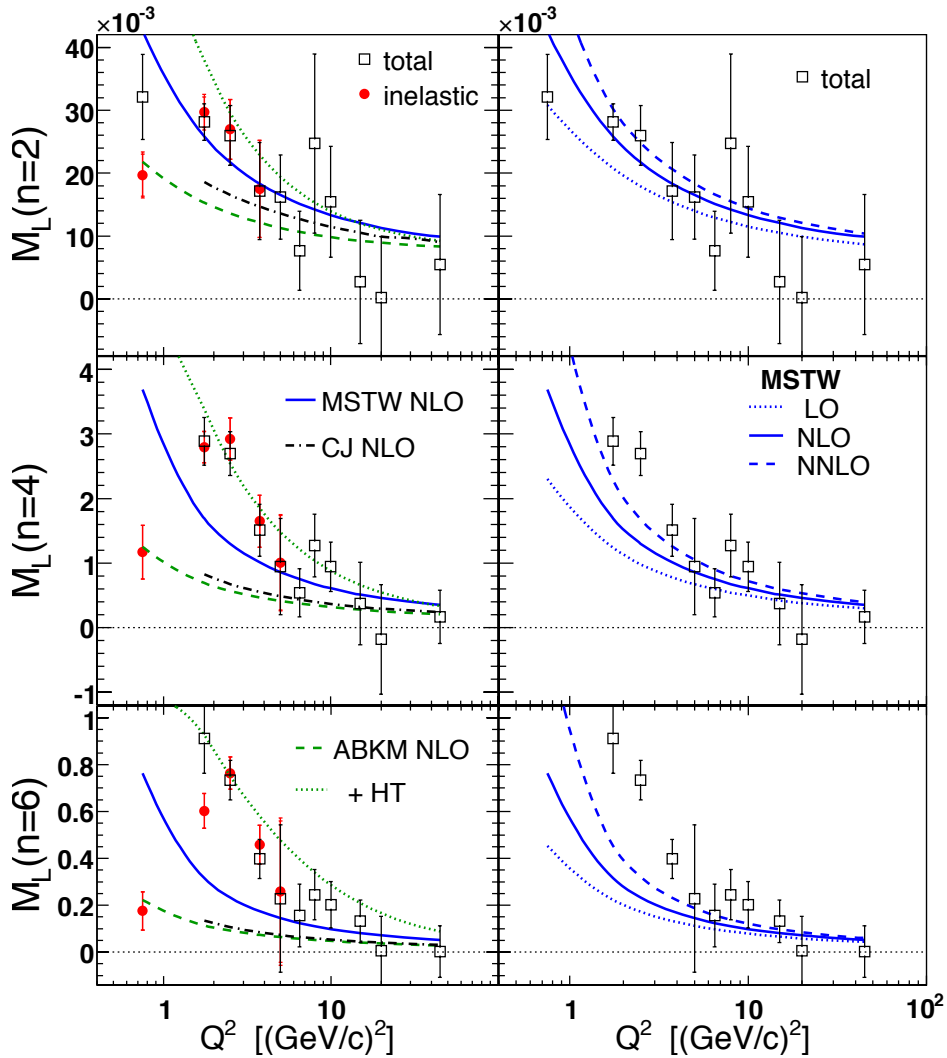
Baillie et al.
PRL ***108****, 142001 (2012)*

→ duality violations < 10% – duality *not* accidental !

→ new approach to DIS at large x: use resonance data to learn about *leading twist* structure!

Inclusive DIS structure functions





Monaghan et al. (2012)

→ longitudinal moment analysis suggests larger gluon distribution at high x

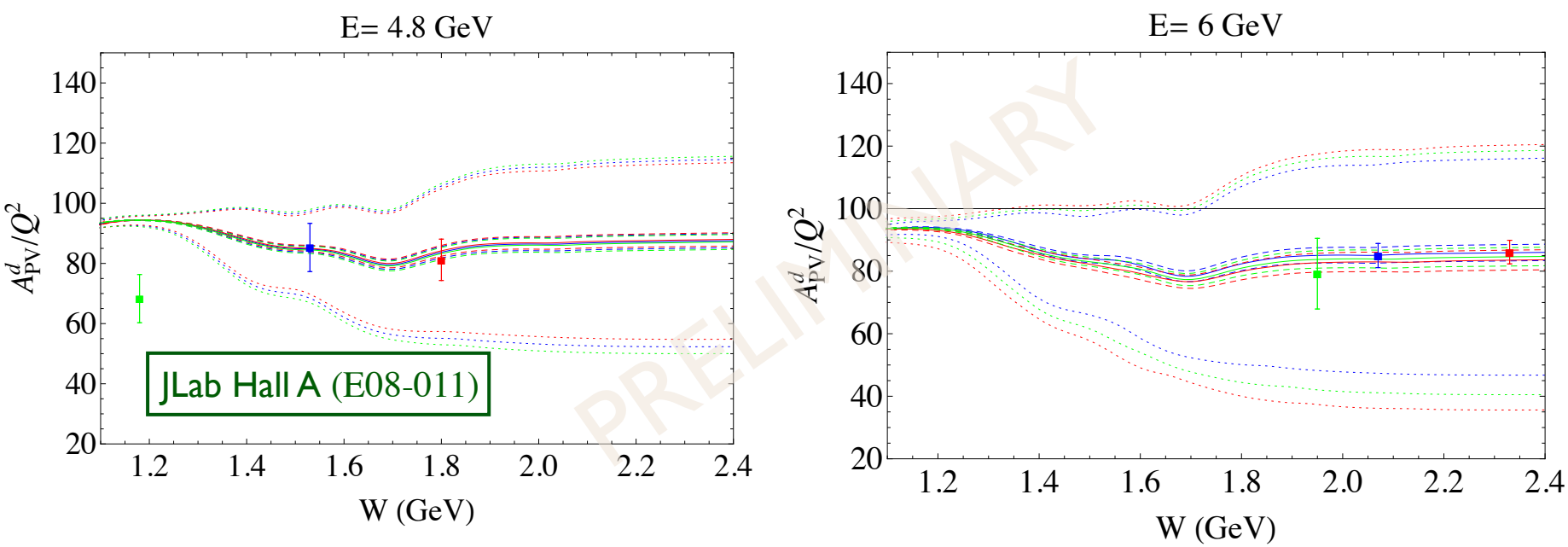
Inclusive PVDIS structure functions

- Left-right polarization asymmetry in $\vec{e}\,p \to e\,p$ scattering

  → depends on γZ interference structure functions

$$A_{\rm PV} = g_A^e \left(\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\right) \frac{xy^2 F_1^{\gamma Z} + (1-y)F_2^{\gamma Z} + \frac{g_V^e}{g_A^e}(y - y^2/2)xF_3^{\gamma Z}}{xy^2 F_1^{\gamma\gamma} + (1-y)F_2^{\gamma\gamma}}$$

  → at large Q^2 sensitive to $1 - 4\sin^2\theta_W$



X. Zheng (2012)

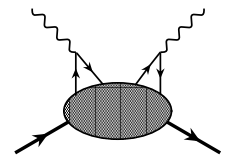
Inclusive DIS structure functions

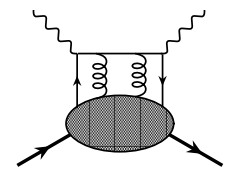
- At *twist-four*, have 3 unique operators

$$\mathcal{O}^V_{\mu\nu} = (\bar{\psi}\gamma_\mu\psi)\,(\bar{\psi}\gamma_\nu\psi)$$

$$\mathcal{O}^A_{\mu\nu} = (\bar{\psi}\gamma_\mu\gamma_5\psi)\,(\bar{\psi}\gamma_\nu\gamma_5\psi)$$

$$\mathcal{O}^g_{\mu\nu} = \bar{\psi}\,\{iD_\mu, \widetilde{F}_{\nu\alpha}\}\gamma_\alpha\gamma_5\,\psi$$





Shuryak, Vainshtein
*NPB **199**, 451 (1982)*

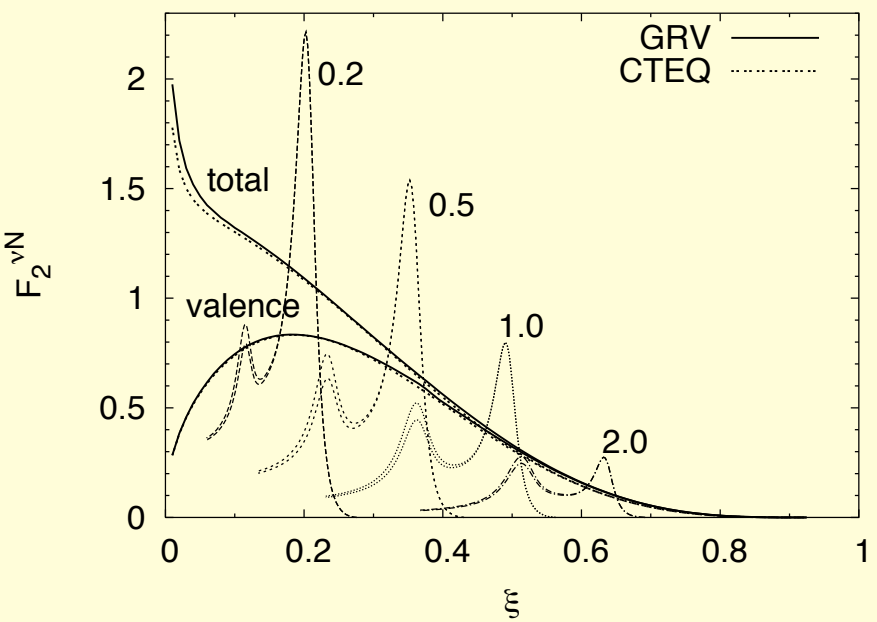
- Higher-twist parts of moments $M_i(Q^2) = \int_0^1 dx\, \mathcal{F}_i(x, Q^2)$ of structure functions $\mathcal{F}_i = F_2, F_L, xF_3$

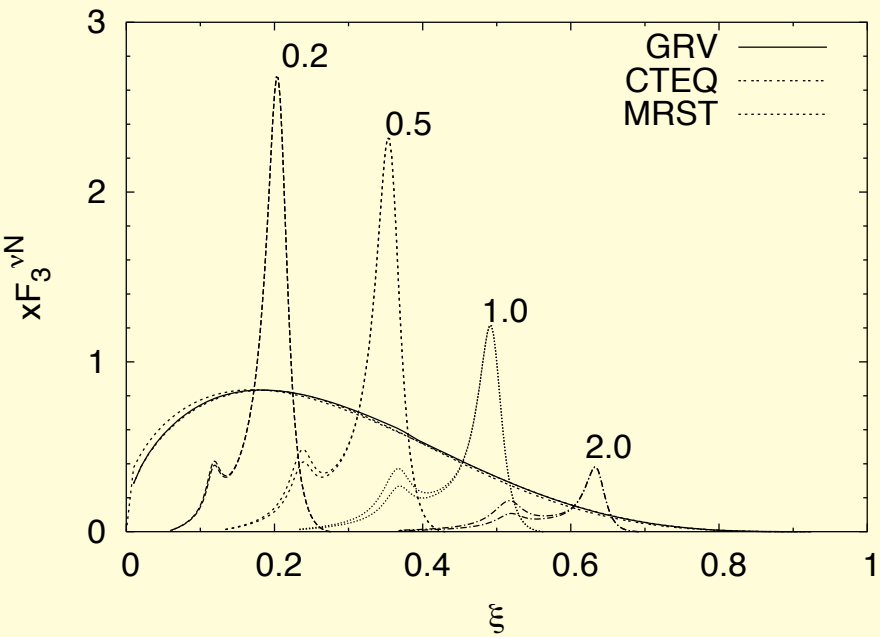
$$M_i^{\rm HT} = c_i^V \langle \mathcal{O}^V \rangle + c_i^A \langle \mathcal{O}^A \rangle + c_i^g \langle \mathcal{O}^g \rangle$$

→ can solve for matrix elements with precise data on moments of all 3 structure functions in $Q^2 \sim 1$–5 GeV^2 region

Complementarity with J-PARC

- Neutrino DIS would allow test of universality of duality, and determine size of higher twist matrix elements in P-odd *vs.* P-even structure functions





Lalakulich, Paschos, WM, PRC ***75****, 015202 (2007)*

→ currently resonance form factors poorly constrained
(old ANL/BNL neutrino resonance-production data)

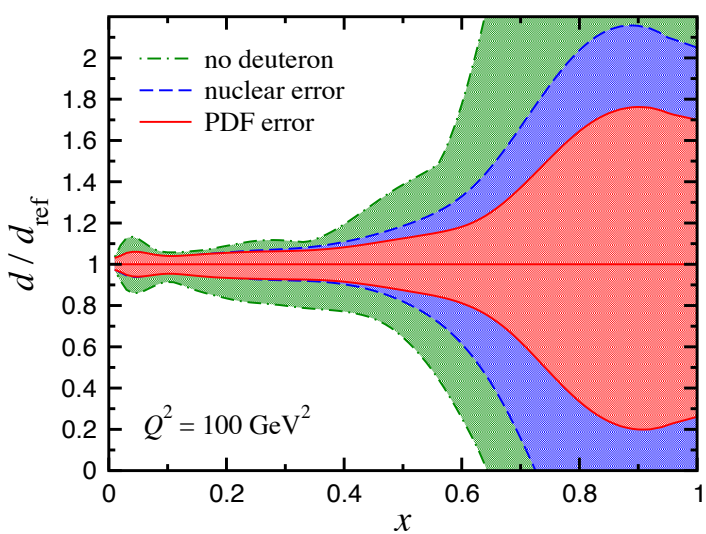
CJ (CTEQ–JLab) global PDF analysis

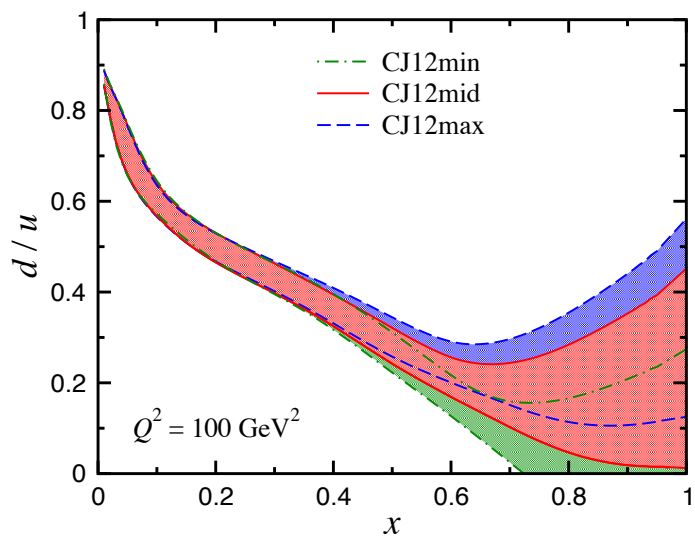
- New global NLO analysis of expanded set of p and d data (DIS, hadronic) including large-x, low-Q^2 region

  → systematic study of effects of Q^2 & W cuts

  → include nuclear & $1/Q^2$ corrections

  → parametrization dependence $(d \rightarrow d + a\,x^b\,u\,)$





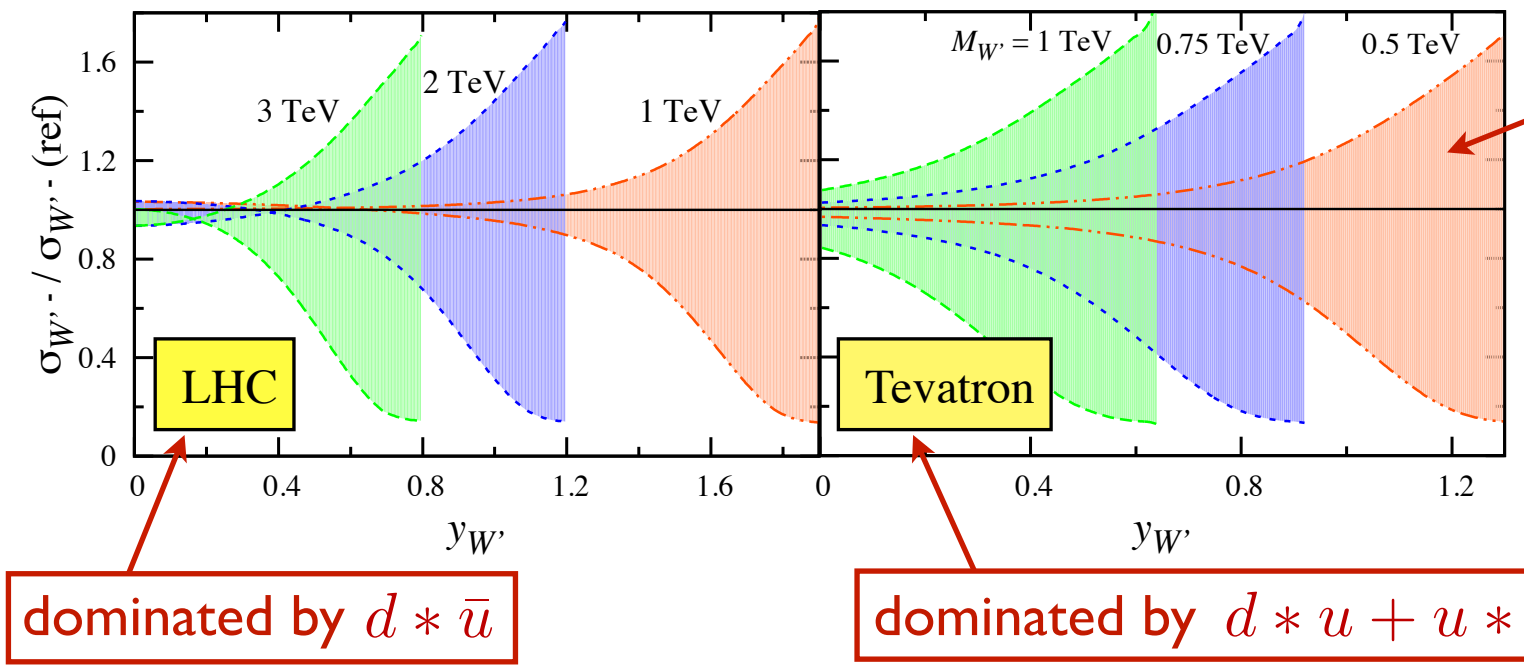
Owens, Accardi, WM, arXiv:1212.1702

http://www.jlab.org/CJ

CJ (CTEQ–JLab) global PDF analysis

- Uncertainty in d-quark feeds into larger uncertainty in *gluon* at high x (important for LHC physics!)

heavy W'^{-} production



> 100% uncertainty at large y !

Brady et al.
JHEP ***1206***, *019 (2012)*

dominated by $d * \bar{u}$

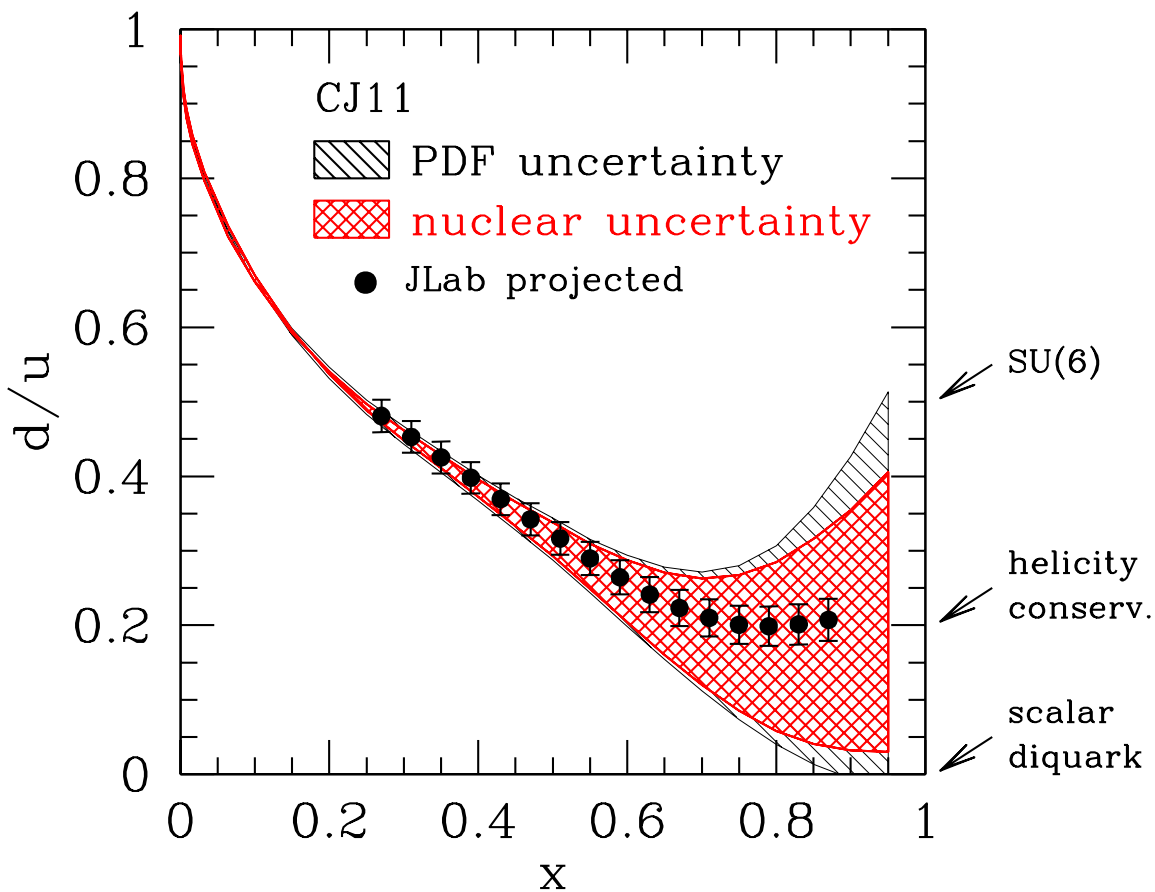
dominated by $d * u + u * d$

→ observation of new physics signals requires accurate determination of QCD backgrounds → depend on PDFs!

JLab 12 GeV plans

- Several planned experiments at JLab with 12 GeV will measure d/u to $x \sim 0.85$ with minimal nuclear corrections

  → SIDIS from D with slow backward proton ("BoNuS"); inclusive ^{3}He / ^{3}H ratio; and PVDIS from proton



Accardi et al., PRD ***84****, 014008 (2011)*

Complementarity with J-PARC

- Cleanest and most direct method is to use neutrino and antineutrino DIS on hydrogen
  (avoid nuclear corrections)

→ selects d and u quark PDFs at large x

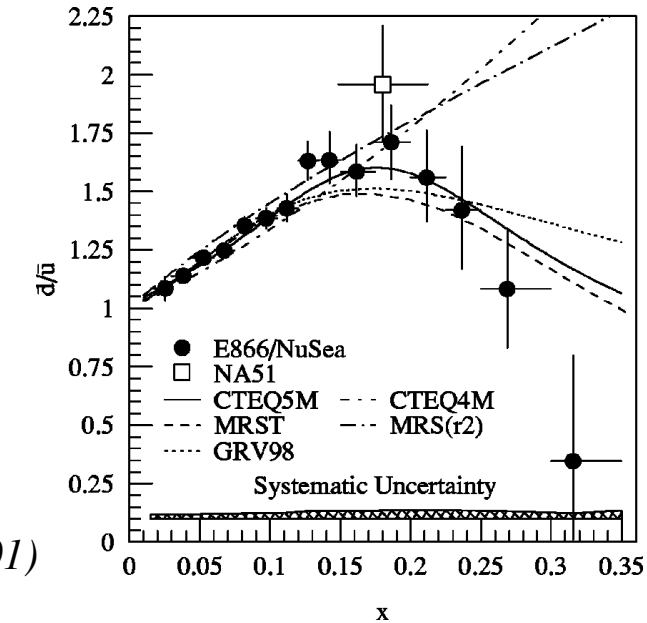
$$\frac{F_2^{\nu p}}{F_2^{\bar{\nu} p}} \rightarrow \frac{d}{u}$$

→ need reach up to $x \sim 0.85$, with large Q^2 range to control for higher twists

Sea quark flavor asymmetry

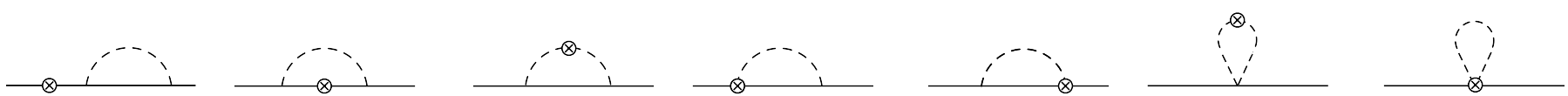
- Flavor asymmetry in proton sea suggests important role of pion cloud in high-energy reactions

  → Drell-Yan process in *pp* & *pd* scattering



*E866, PRD **64**, 052002 (2001)*

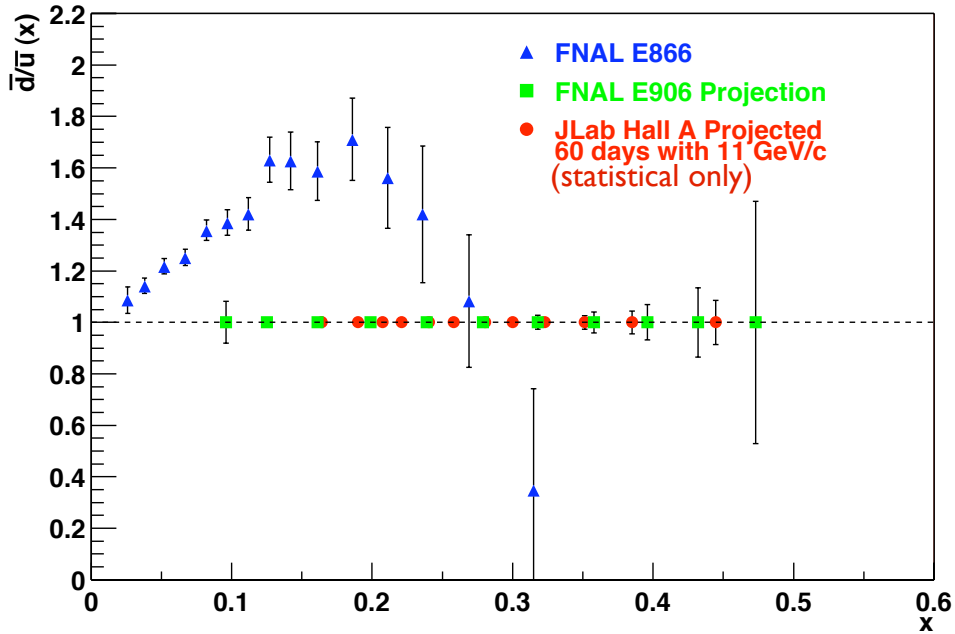
- Compute pion (& nucleon) distribution functions in χPT



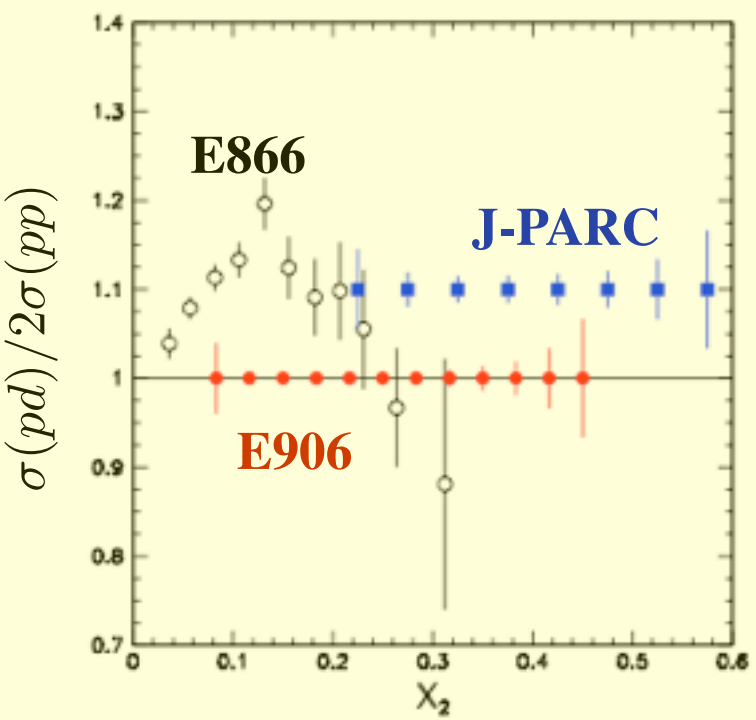
Burkardt et al., arXiv:1211.5853

- Can also be measured in semi-inclusive $\pi^{\pm}$ production from protons or deuterons

JLab 12 GeV plans

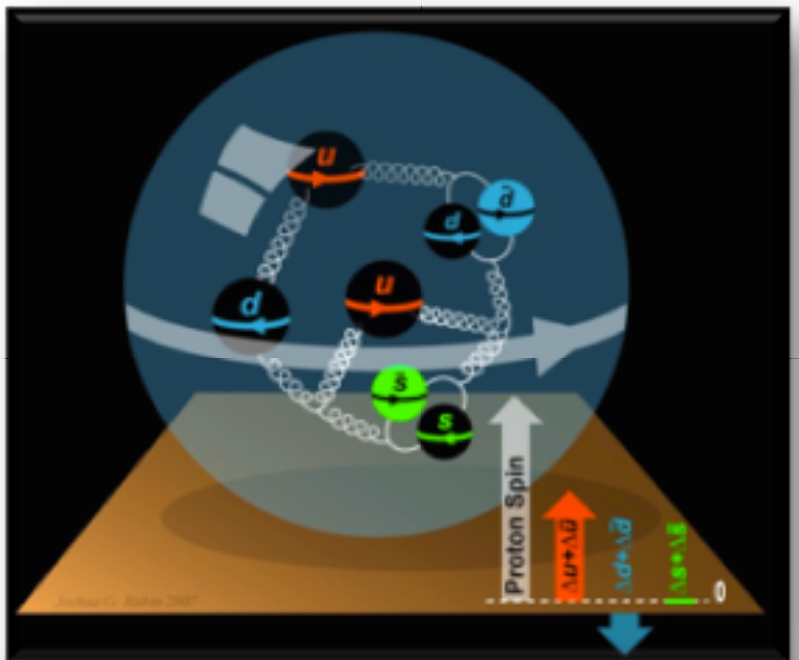


Complementarity with J-PARC



→ talk of Shunzo Kumano

Nucleon spin structure

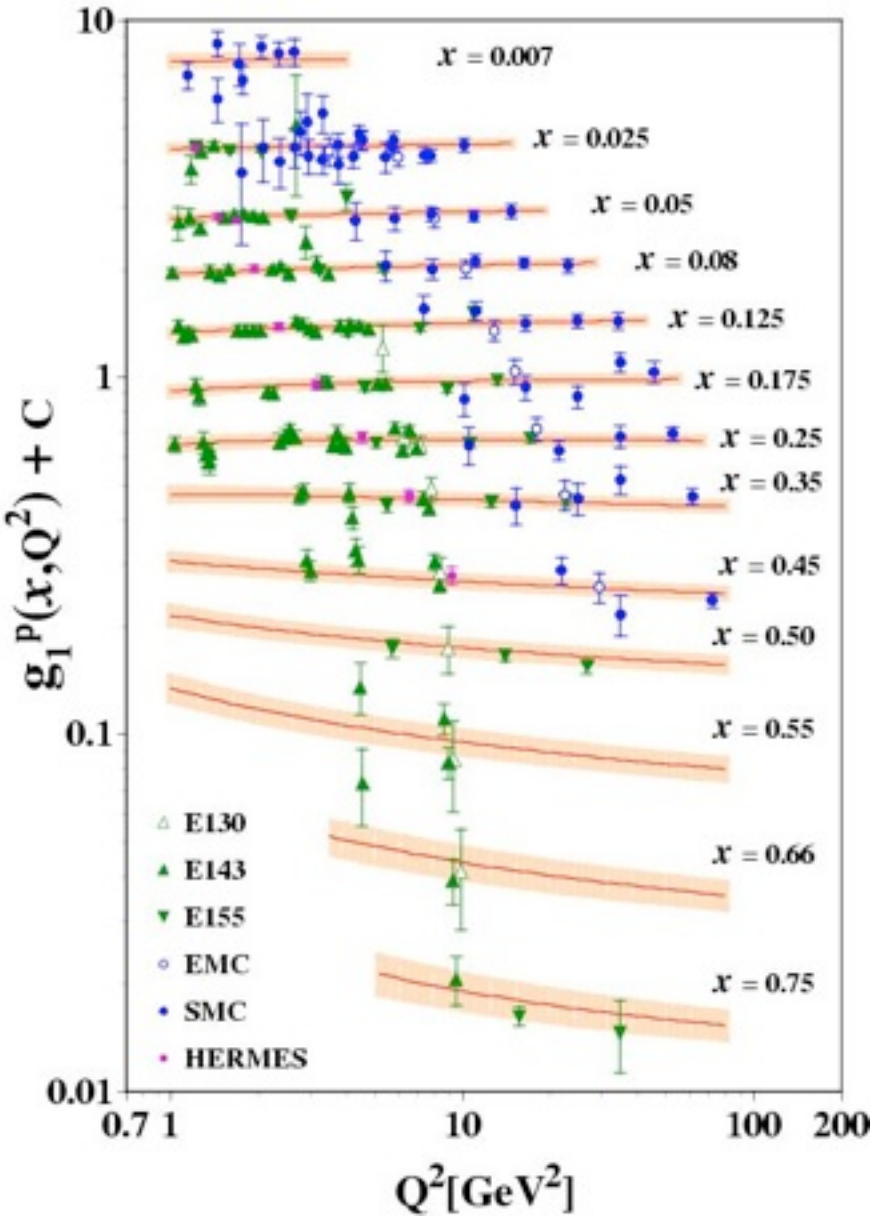


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

$\Delta\Sigma \sim 0.25$ (DIS)

$\Delta G \ll 1$ (DIS + pp)

$L_{q,g} = ?$ (GPDs)



→ world DIS data before JLab

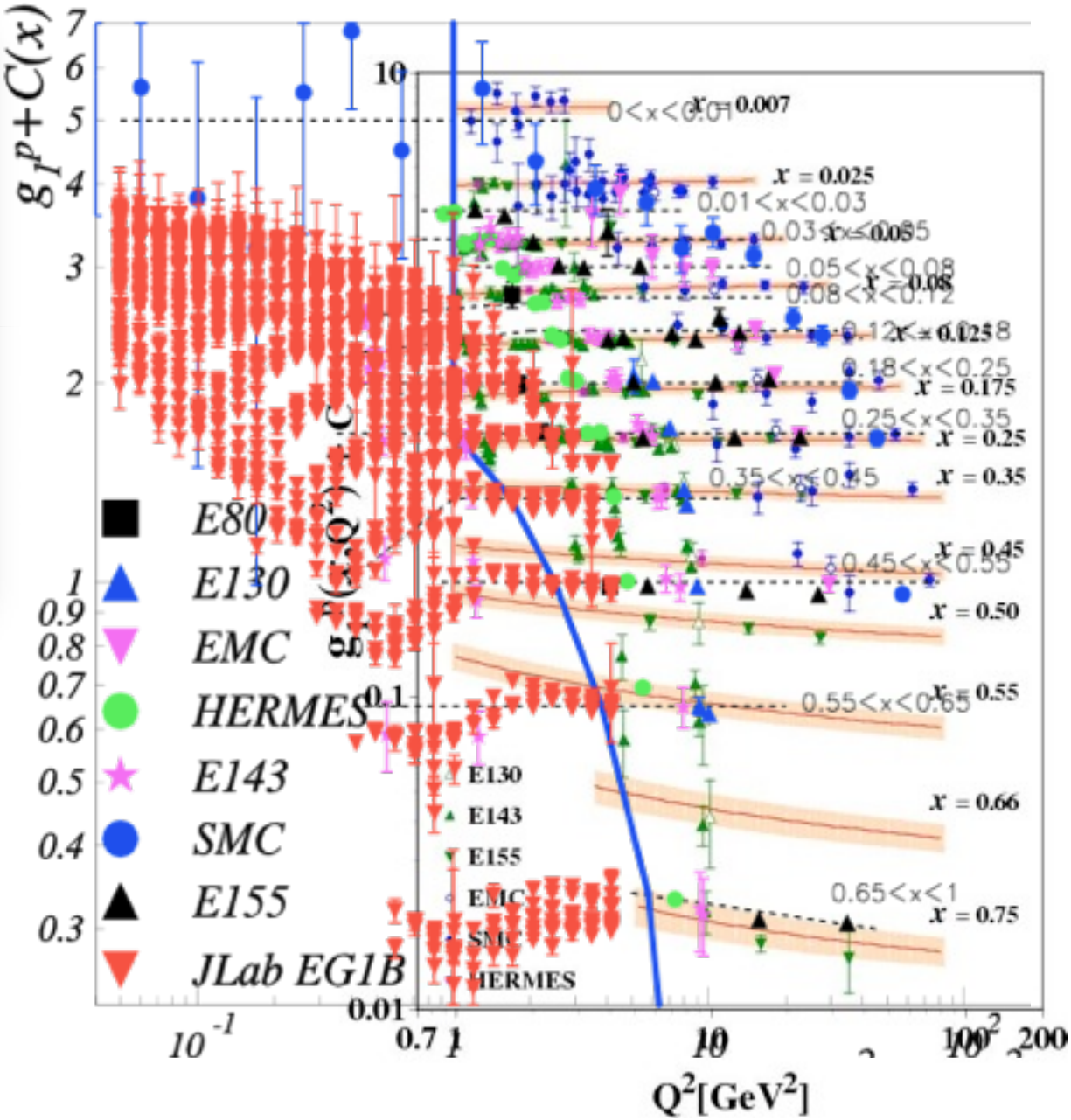
Nucleon spin structure

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

$\Delta\Sigma \sim 0.25$ (DIS)

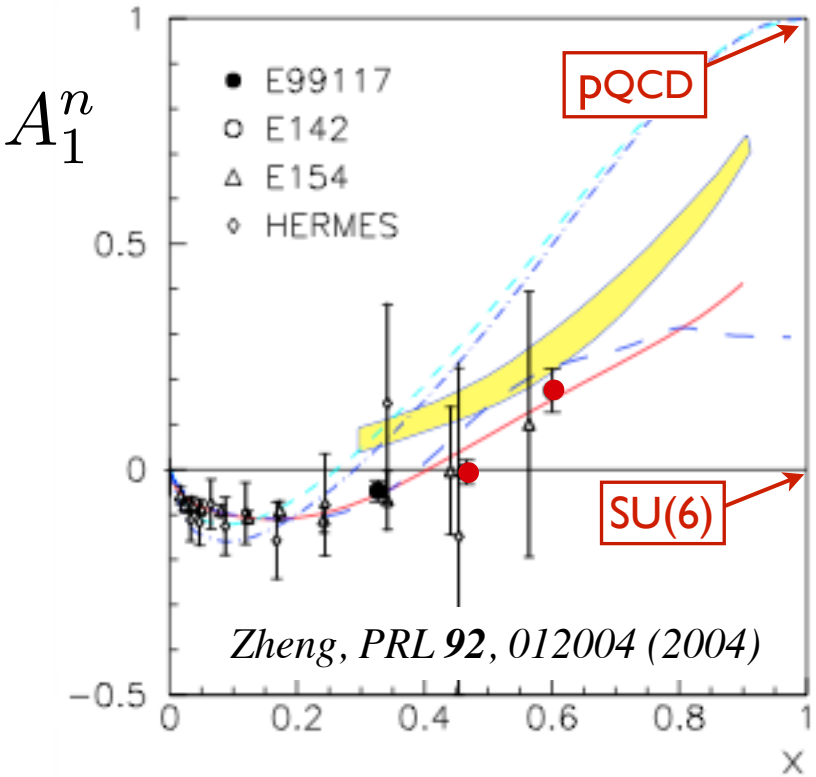
$\Delta G \ll 1$ (DIS + pp)

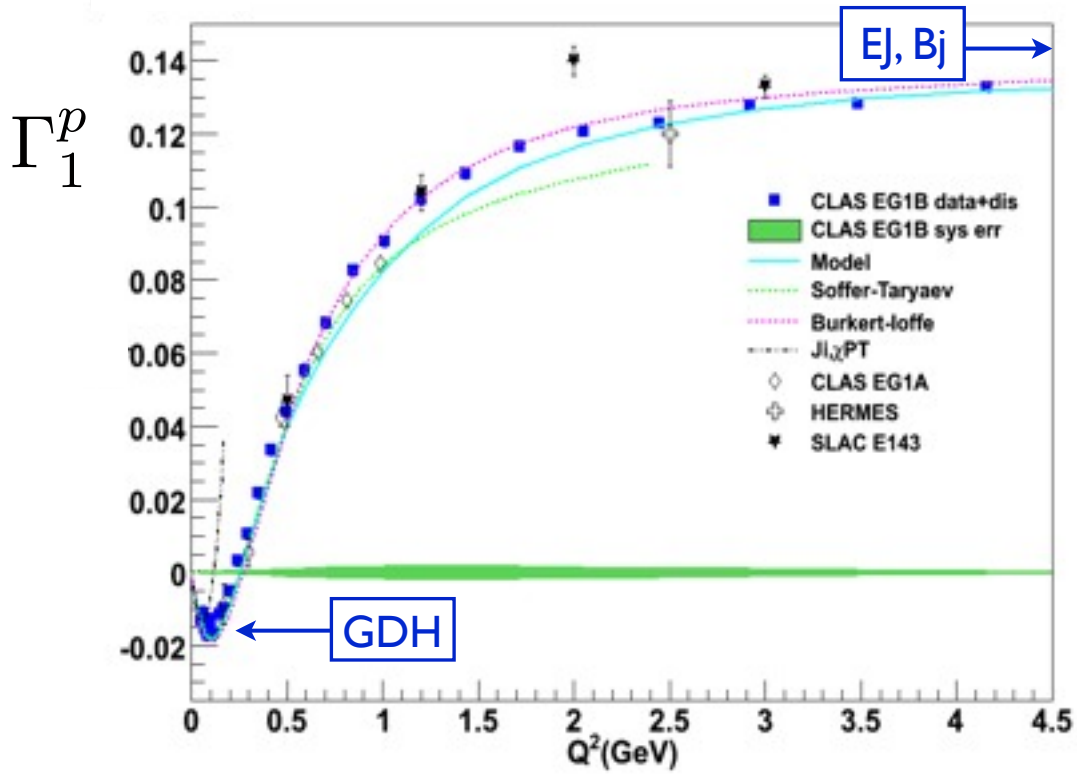
$L_{q,g} = ?$ (GPDs)



→ world data with JLab (up to ~ 2011)

Nucleon spin structure





→ first evidence of rise above unity

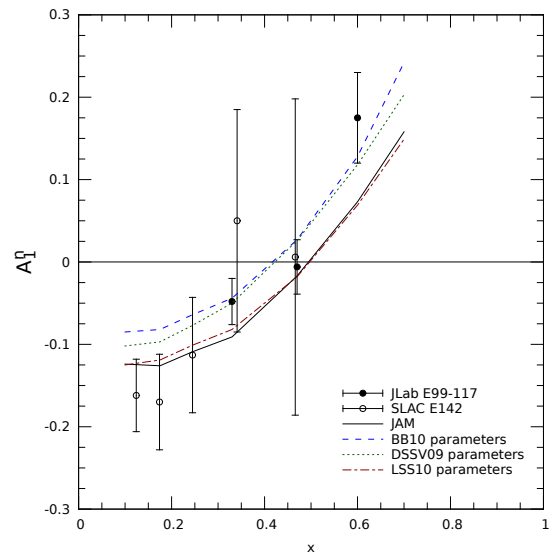
(dramatic difference between pQCD & SU(6) predictions)

→ evaluation of moments maps transition from pQCD to EFT

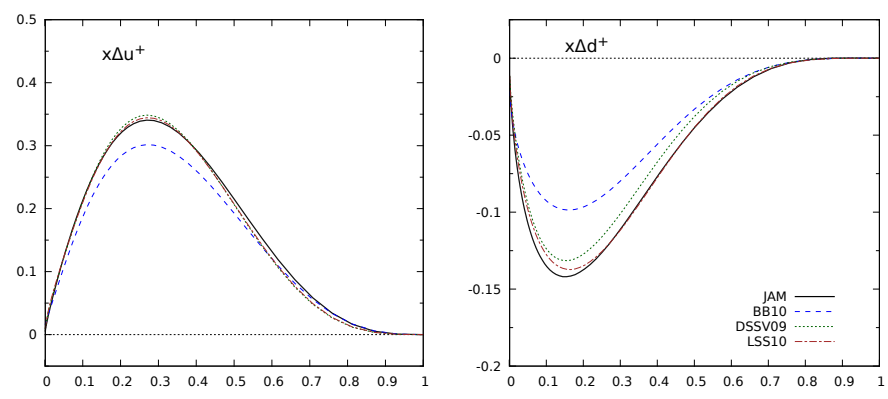
(test sum rules, lattice QCD)

JAM global PDF analysis*

- Utilize high-precision low-W, low-Q^2 JLab data to constrain spin PDFs at large x, systematically including
  - → dependence on W & Q^2 cuts
  - → finite-Q^2 corrections
  - → nuclear smearing corrections



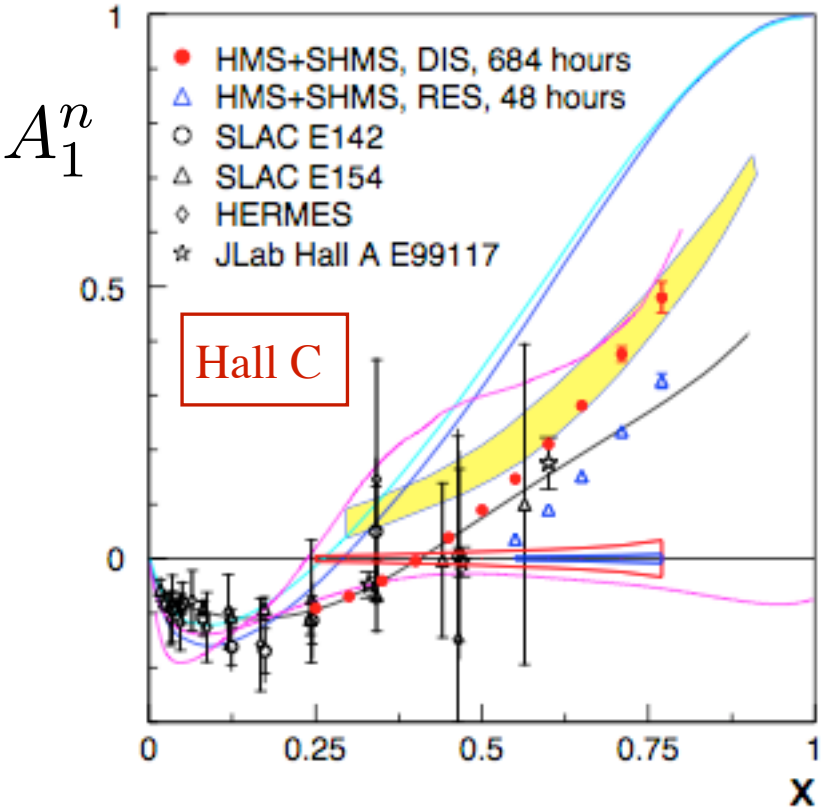
- How does $\Delta q/q$ behave as $x \to 1$?
  - → is there evidence for $L_z = 1$ component of wave function from $\Delta d(x)$?



Jimenez-Delgado et al. (2013)

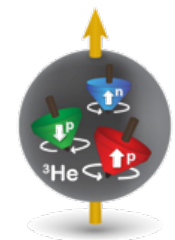
* JLab Angular Momentum collaboration:
http://www.jlab.org/JAM

JLab 12 GeV plans



Flagship 12 GeV experiment

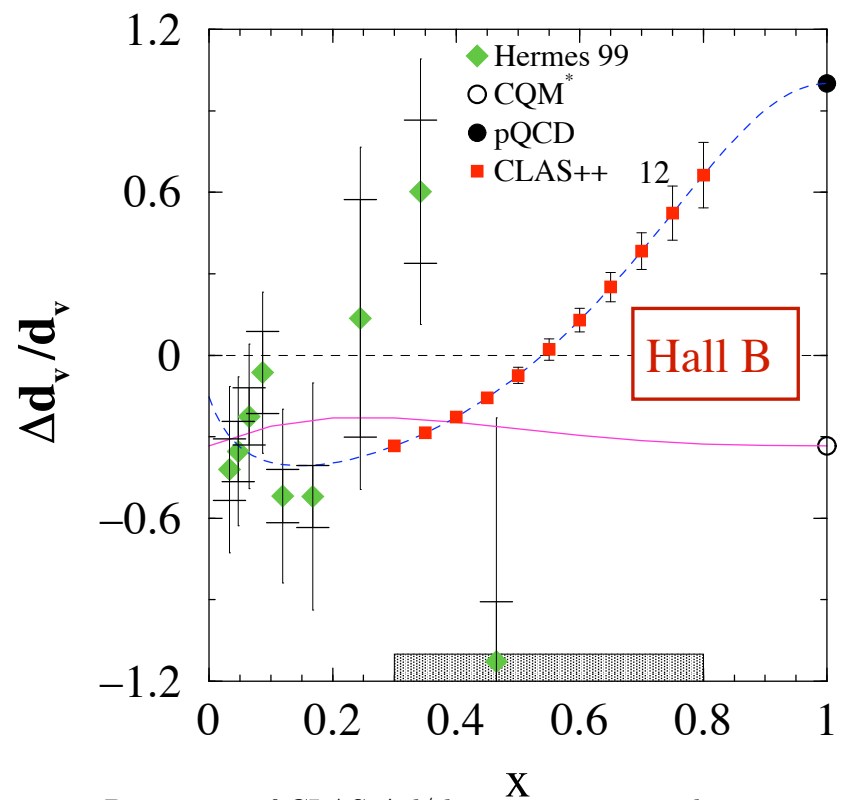
^{3}He target



$x \leq 0.77$

$2.8 \lesssim Q^2 \lesssim 10.5\ \mathrm{GeV}^2$

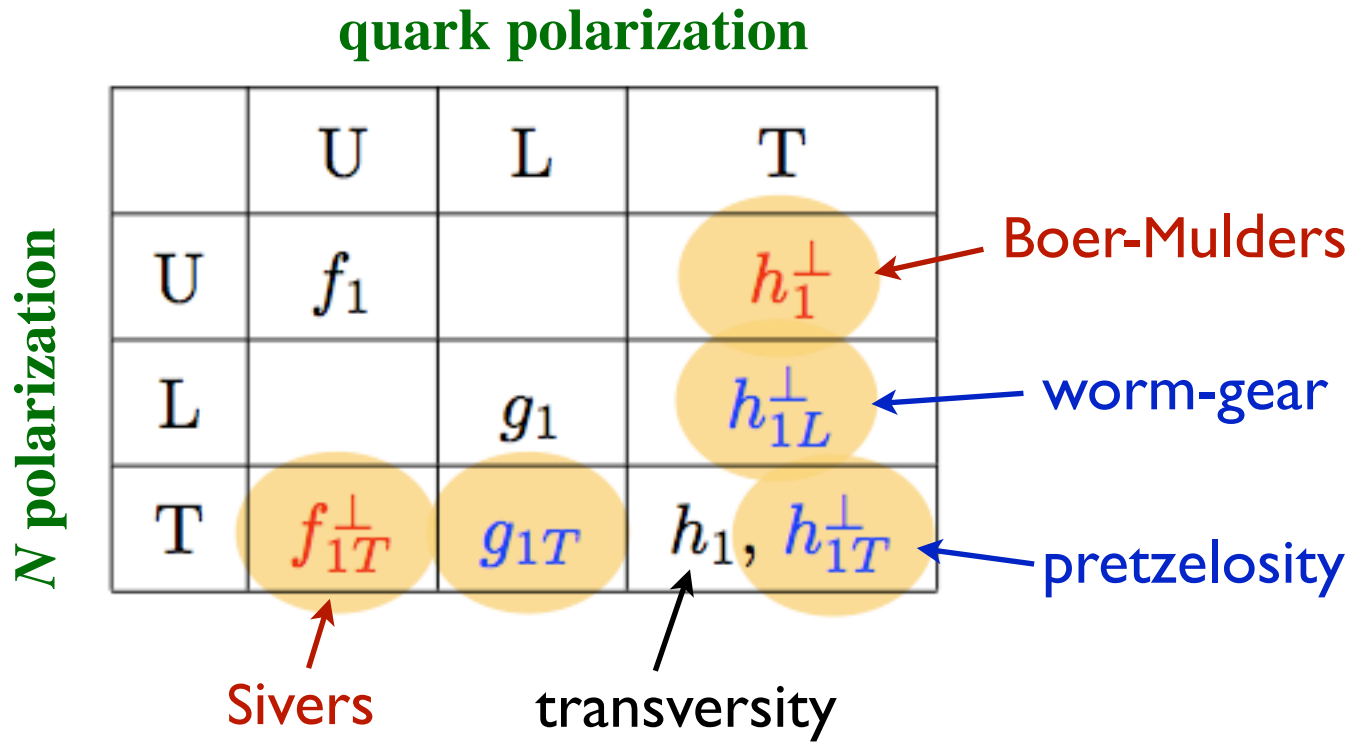
semi-inclusive $\pi^{\pm}$ production from p & d



Transverse Nucleon Structure

TMDs

- Including transverse momentum of partons in nucleon, there exist eight twist-2 distribution functions

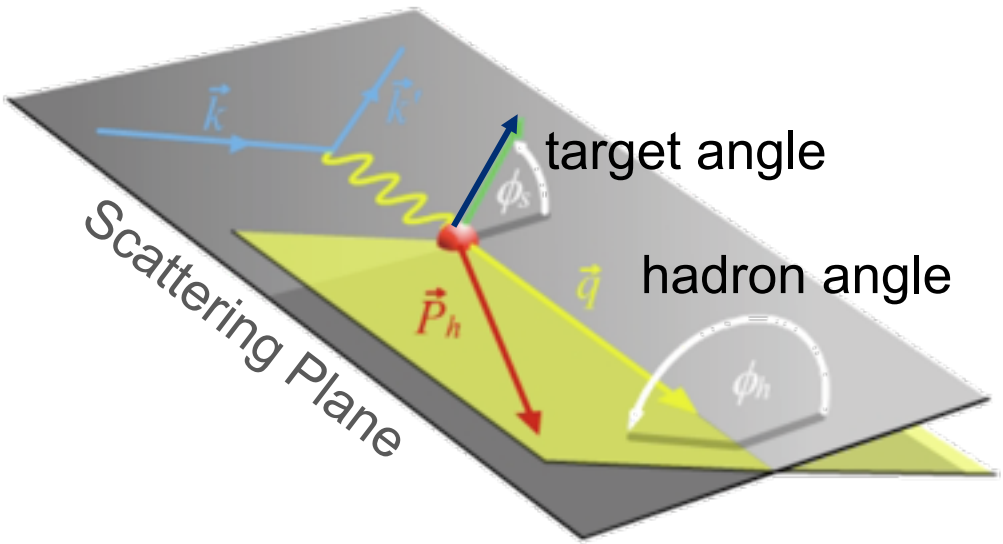


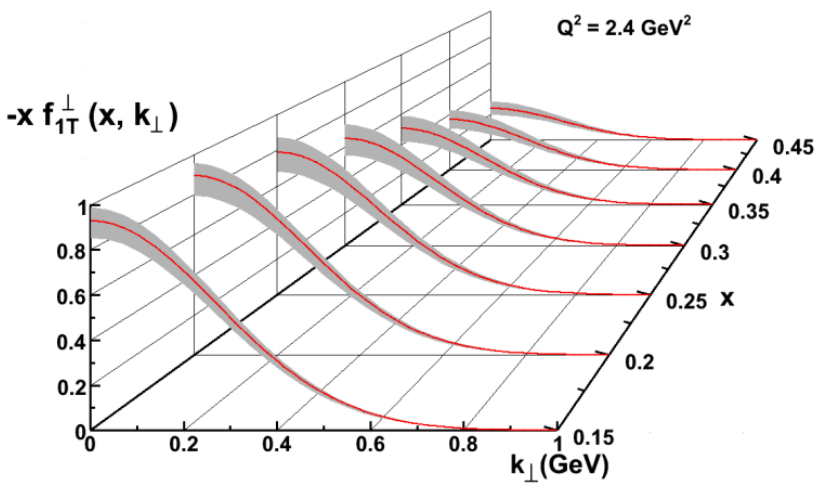
→ window on parton orbital angular momentum (OAM)

→ measured through single & double spin asymmetries in SIDIS and *pp* scattering

TMDs

- Extract Sivers function in pion SIDIS from azimuthal angle distributions





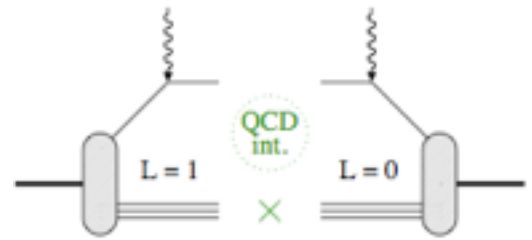
→ Sivers angle $(\phi_h - \phi_s)$ — effect in distribution function

→ Collins angle $(\phi_h + \phi_s)$ — effect in fragmentation function

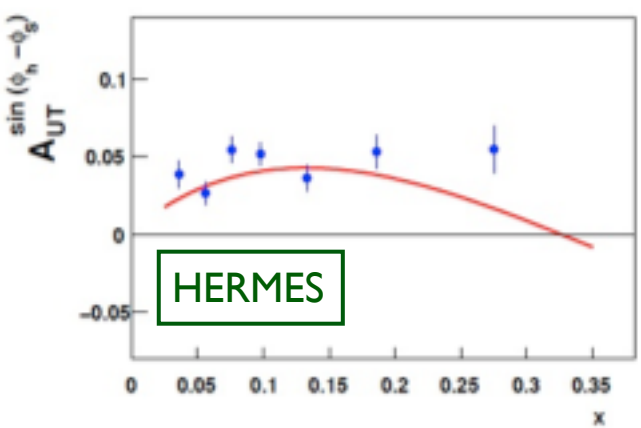
TMDs: Sivers

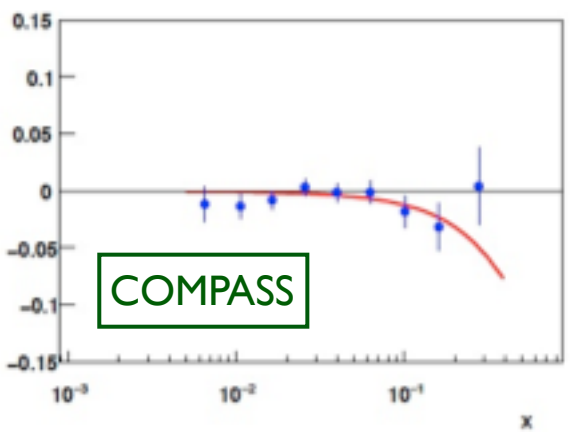
- T-odd distribution, until recently thought to vanish

→ first estimates of proton A_{UT} asymmetries



interference structure function between states of different OAM

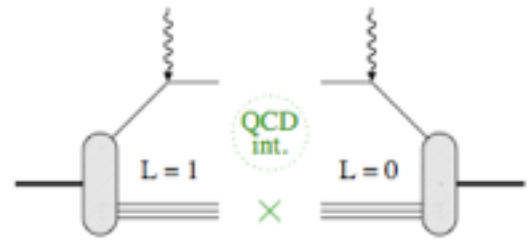




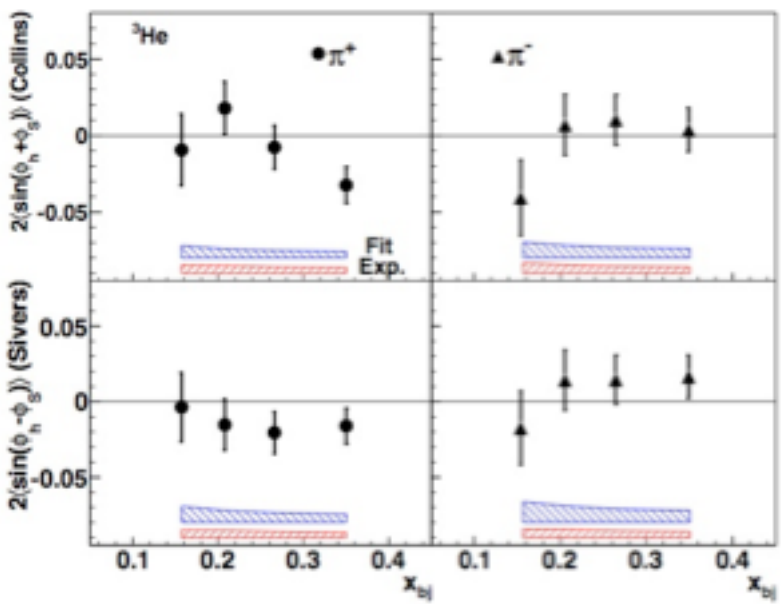
TMDs: Sivers

- T-odd distribution, until recently thought to vanish

→ first estimates of neutron A_{UT} asymmetries



interference structure function between states of different OAM



JLab Hall A

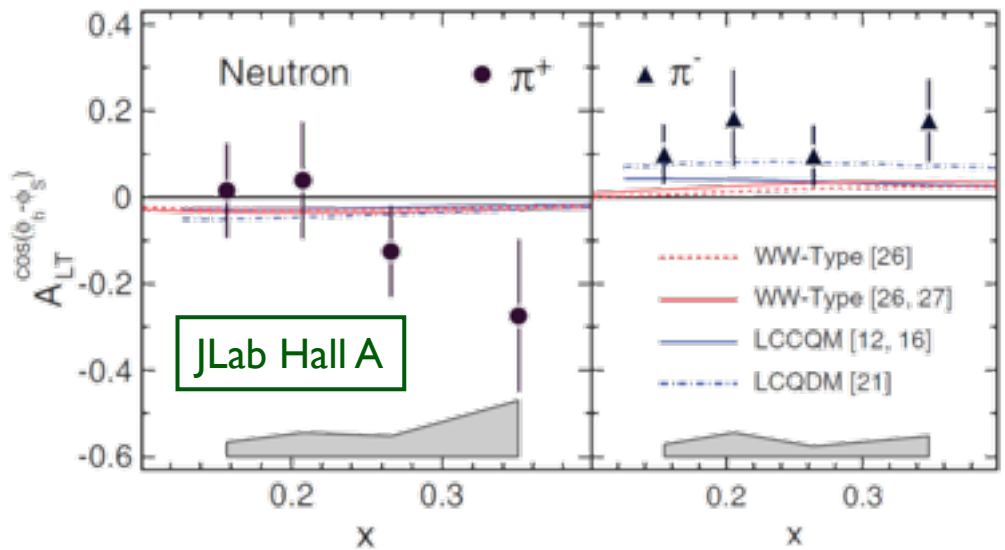
Qian et al., PRL ***107****, 072003 (2011)*

- Different path in gauge link leads to opposite sign in SIDIS and DY

$$f_{1T}^{\perp}\Big|_{\mathrm{DY}} = -f_{1T}^{\perp}\Big|_{\mathrm{SIDIS}}$$

TMDs: worm-gear

- Beam-target double spin asymmetry



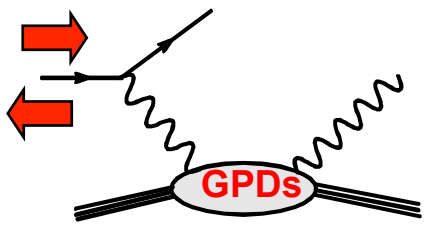
Huang et al.
PRL ***108****, 052001 (2012)*

→ indicates nonzero quark orbital motion
(quark *longitudinal* spin distribution
in *transversely* polarized nucleon)

→ set up framework for future global (SIDIS, DY, e^+e^-)
fits of TMDs (extension of CJ/JAM PDF analysis)

GPDs

- Deeply virtual Compton scattering (DVCS)



unpolarized H, E
polarized $\widetilde{H}, \widetilde{E}$
} functions of x, ξ, t, Q^2

$$\xi = \frac{x_B}{2 - x_B}$$

→ Ji sum rule

$$\int_{-1}^{1} dx\, x\, (H_q + E_q)_{t=0} = J_q$$

→ various spin combinations sensitive to different GPDs

$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1 H + \xi(F_1+F_2)\,\widetilde{H} - kF_2 E\}d\phi$

$\Delta\sigma_{UL} \sim \sin\phi\ \mathrm{Im}\{F_1 H + \xi(F_1+F_2)\,(H + x_B E/2) - \xi k F_2\, E + \ldots\}d\phi$

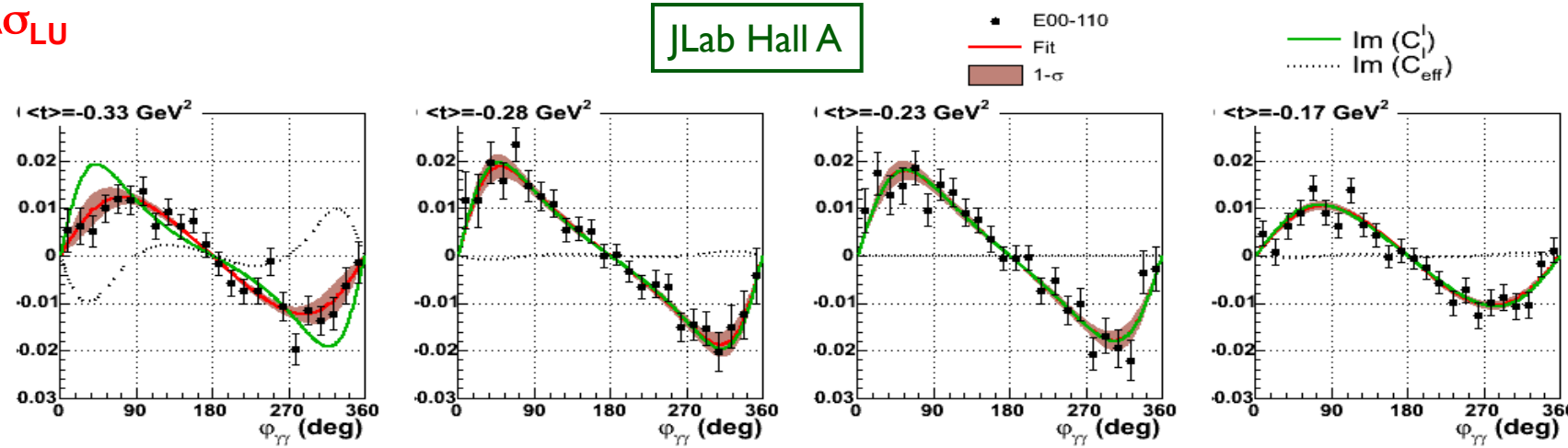
$\Delta\sigma_{LL} \sim (A + B\cos\phi)\ \mathrm{Re}\{F_1 H + \xi(F_1+F_2)\,(H + x_B E/2)\ldots\}d\phi$

$\Delta\sigma_{UT} \sim \cos\phi\ \mathrm{Im}\{k\,(F_2 H - F_1 E) + \ldots..\}d\phi$

GPDs

$\Delta\sigma_{LU}$

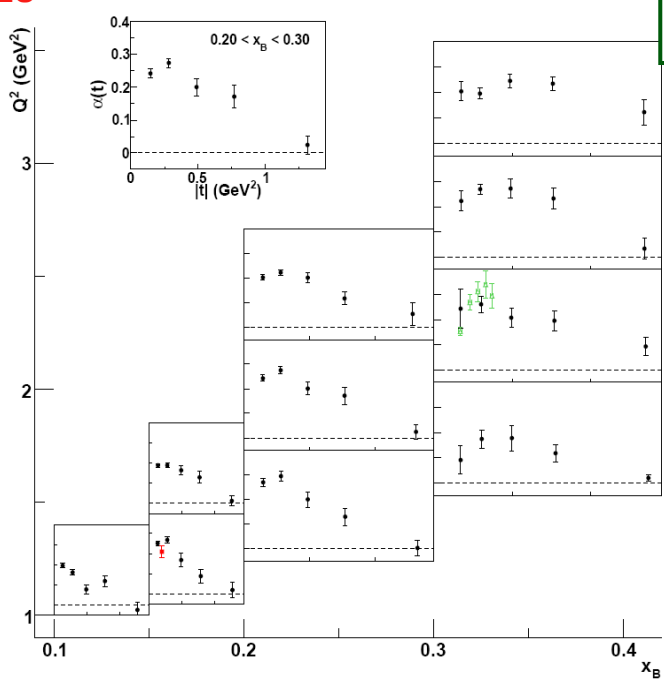
JLab Hall A



*PRL **97**, 262002 (2006)*

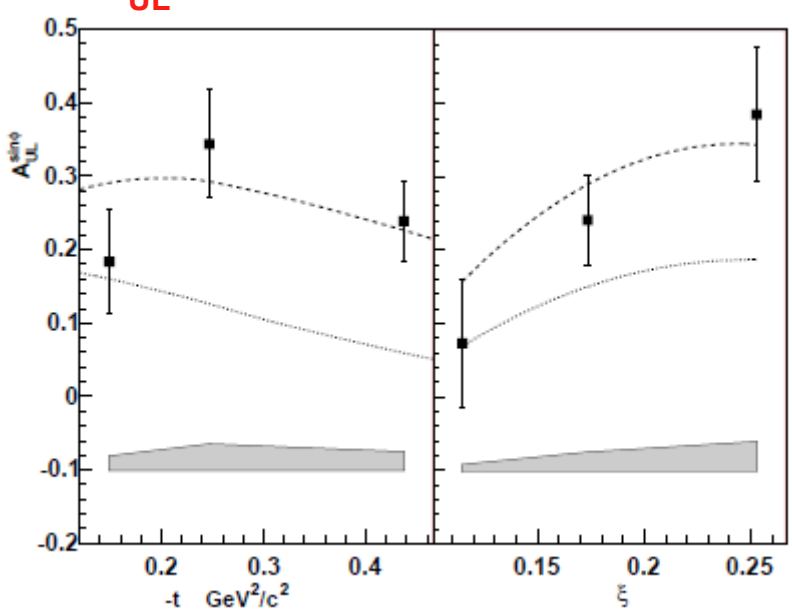
A_{LU}

JLab Hall B



*PRL **100**, 162002 (2008)*

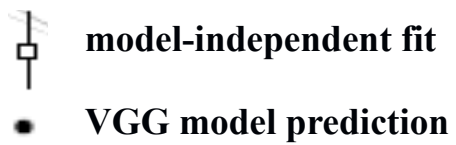
A_{UL}

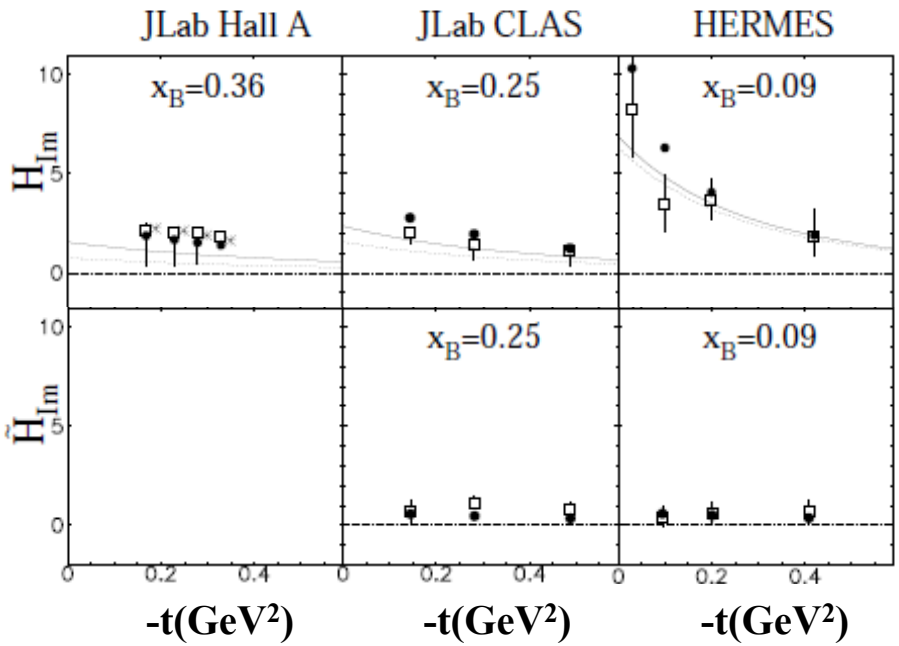


*PRL **100**, 162002 (2008)*

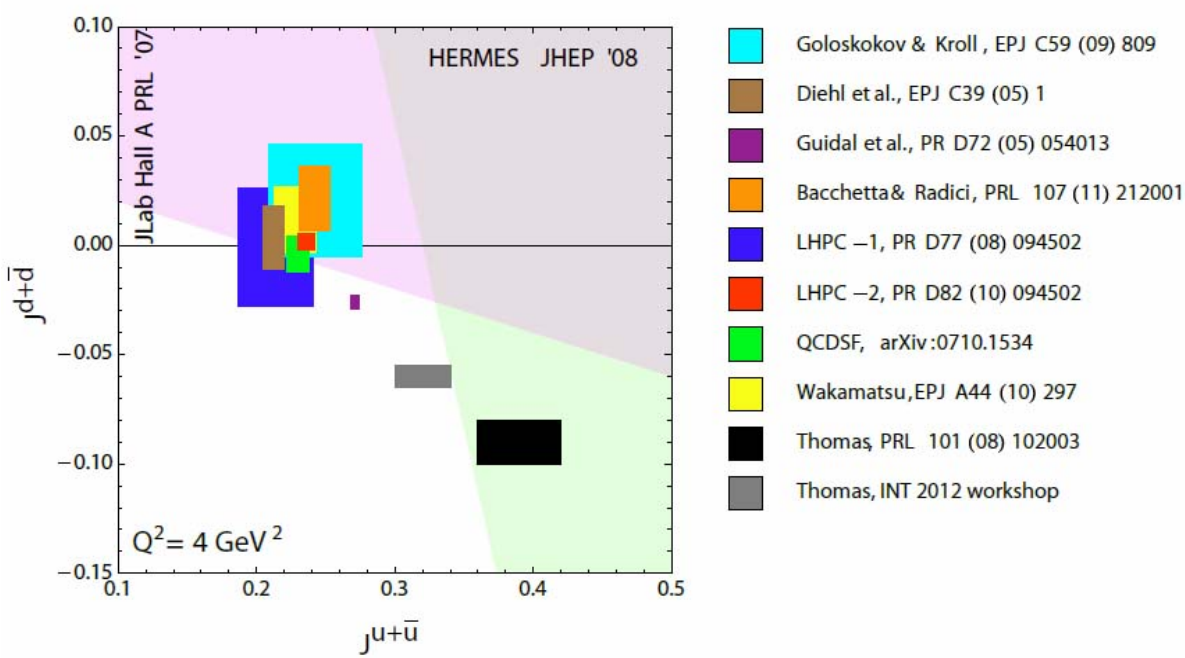
GPDs

- Model-independent fit to world's DVCS data





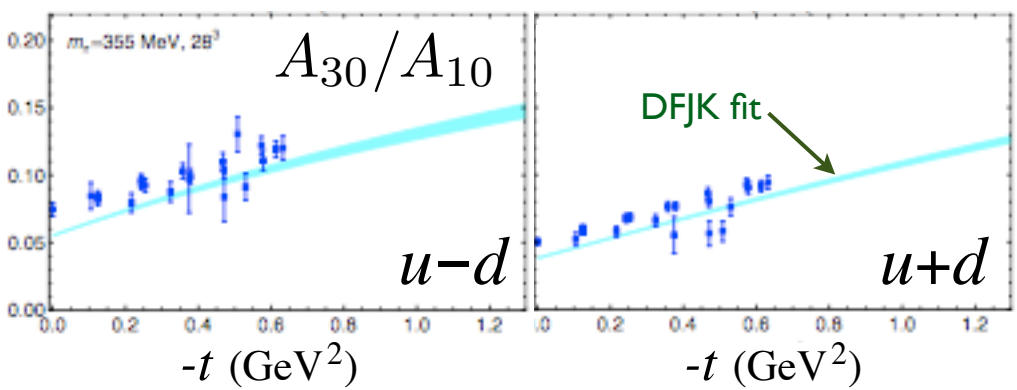
- Extraction of total angular momentum *J* carried by quarks
  - → from quark helicity measured in DIS, deduce orbital angular momentum



GPDs: lattice moments

generalized form factors

$$A_{n0} \sim \int dx\, x^{n-1} H(x,\xi,t)$$



Lattice Hadron Physics Collaboration
PRD 77, 094502 (2008)

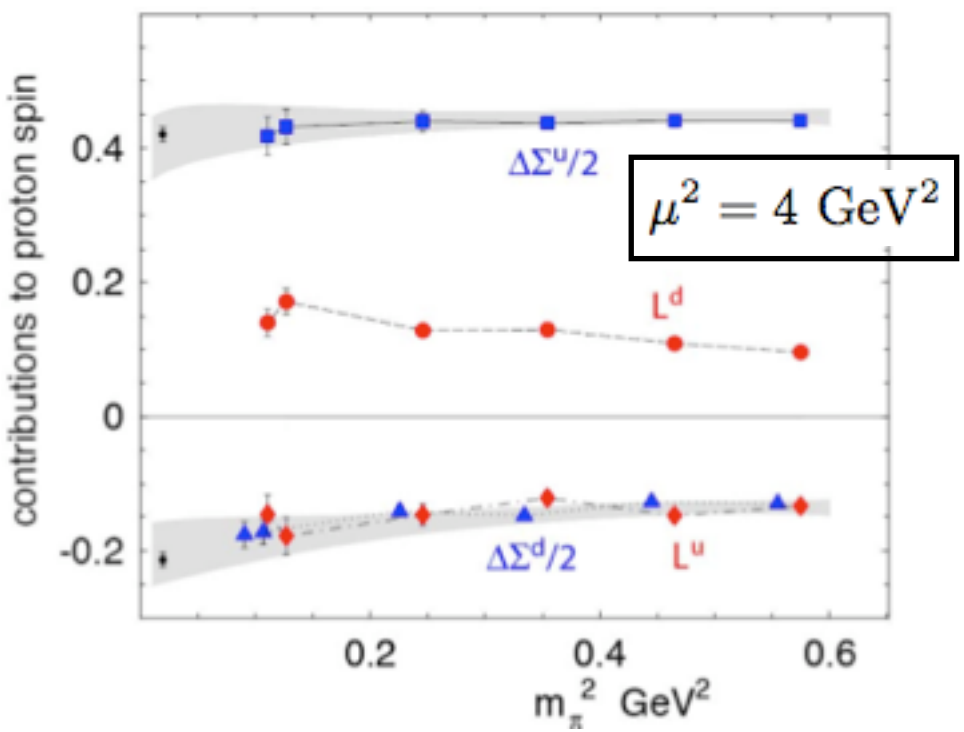
→ lattice data will constrain GPD parameterizations

→ talk of Huey-Wen Lin

nucleon spin

$$J^q = \left(A^q_{20}(0) + B^q_{20}(0)\right)/2$$

$$L^q = J^q - \Delta\Sigma^q/2$$



$$L^{u+d} \approx 0\ , \quad L^d \approx -L^u \approx 30\%$$

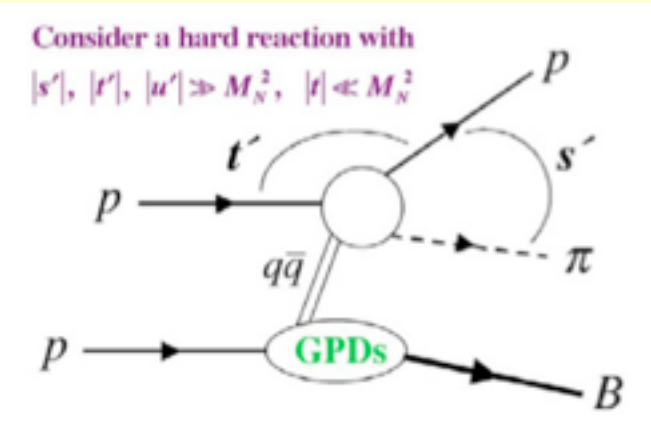
$$J^{u+d} \approx 40-50\%\ , \quad J^d \approx 0$$

Complementarity with J-PARC

- Novel idea to study GPDs in hadronic pp reactions

  → access to ERBL region $(-\xi < x < \xi)$

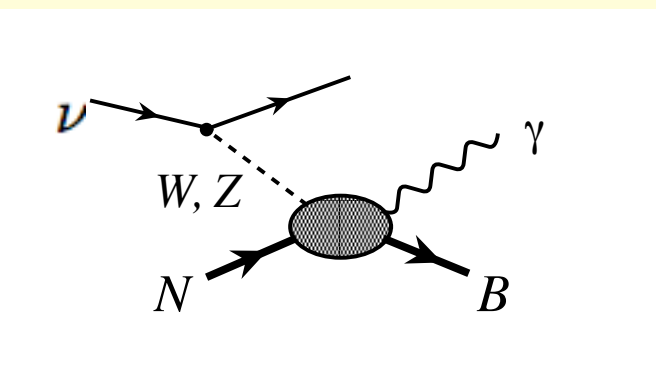
  → flavor decomposition, non-diagonal transitions



Kumano, Strikman, Sudoh
PRD ***80****, 074003 (2009)*

- Neutrino DVCS uniquely sensitive to $C-odd$ combinations of GPDs, not accessible with e scattering

  → can extract *spin-dependent* valence & sea distributions with an unpolarized target!

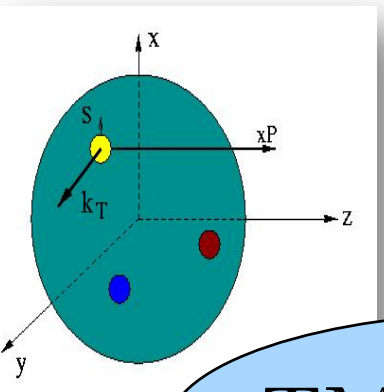


Psaker, WM, Radyushkin
PRD ***75****, 054001 (2007)*

Hierarchy of nucleon structure

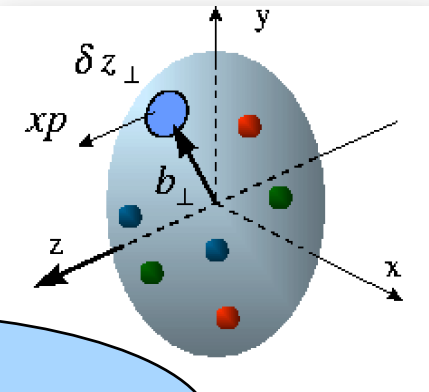
Wigner distribution

$W(x, \mathbf{k}_\perp, \mathbf{b}_\perp)$ **5D**



$\int d^2\mathbf{b}_\perp$ $\int d^2\mathbf{k}_\perp$

$\mathrm{TMD}(x, \mathbf{k}_\perp)$ **3D** $\mathrm{GPD}(x, \xi, t)$



$\int d^2\mathbf{k}_\perp$ $t \to 0$ $\int dx$

$\mathrm{PDF}(x)$ **1D** $\mathrm{FF}(t)$

Outlook

12 GeV Upgrade of CEBAF

- Role of gluonic excitations in (light) meson spectroscopy?
  (→ quark confinement)

- Missing spin of the proton: is there significant quark orbital angular momentum?

- Novel landscape of nucleon substructure through new multidimensional distributions
  (→ PDFs, GPDs, TMDs)

- Relation between short-range NN corrections and partonic structure of nuclei?

- Evidence for physics beyond the standard model?

12 GeV Upgrade of CEBAF

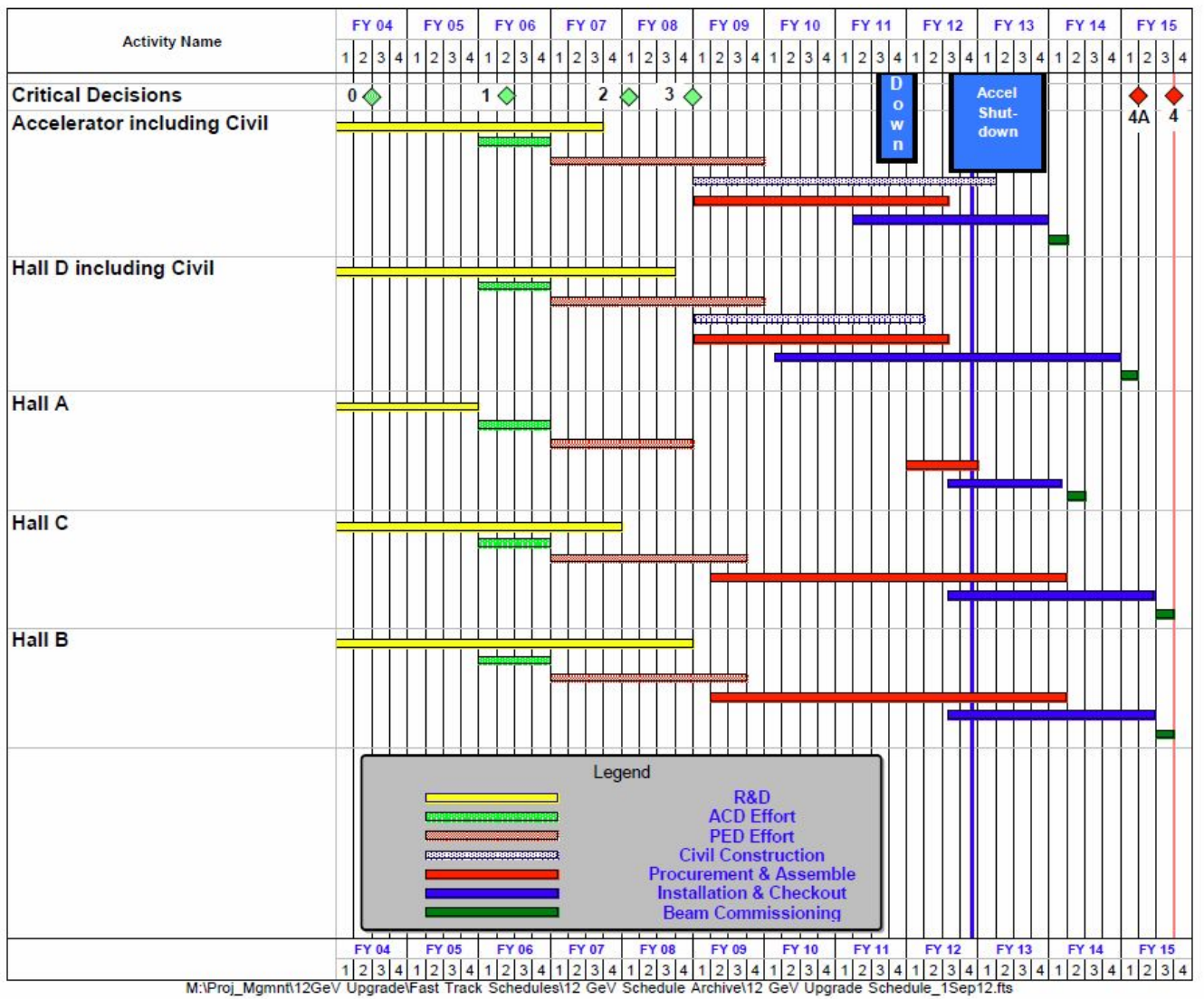
Approved experiments

Topic	Hall A	Hall B	Hall C	Hall D	Total
The Hadron spectra as probes of QCD (GluEx and heavy baryon and meson spectroscopy)		1		1	2
The transverse structure of the hadrons (Elastic and transition Form Factors)	4	3	2		9
The longitudinal structure of the hadrons (Unpolarized and polarized parton distribution functions)	2	2	5		9
The 3D structure of the hadrons (Generalized Parton Distributions and Transverse Momentum Distributions)	5	10	3		18
Hadrons and cold nuclear matter (Medium modification of the nucleons, quark hadronization, F N-N correlations, hypernuclear spectroscopy, few-body experiments)	3	2	6		11
Low-energy tests of the Standard Model and Fundamental Symmetries	2			1	3
Total	**16**	**18**	**16**	**2**	**52**

→ more than 7 years of running time already approved!

12 GeV Upgrade of CEBAF

Current 12 GeV schedule



FY12: reduction of $16M
FY13: Pres Request – no restoration
CD-4B may be at Risk

16 month installation
May 2012 – Sep 2013

Hall A commissioning start
Feb 2014

Hall D commissioning start
Oct 2014

Halls B & C commissioning start Apr 2015

Project Completion
June 2015

Electron Ion Collider

NSAC 2007 Long-Range Plan:

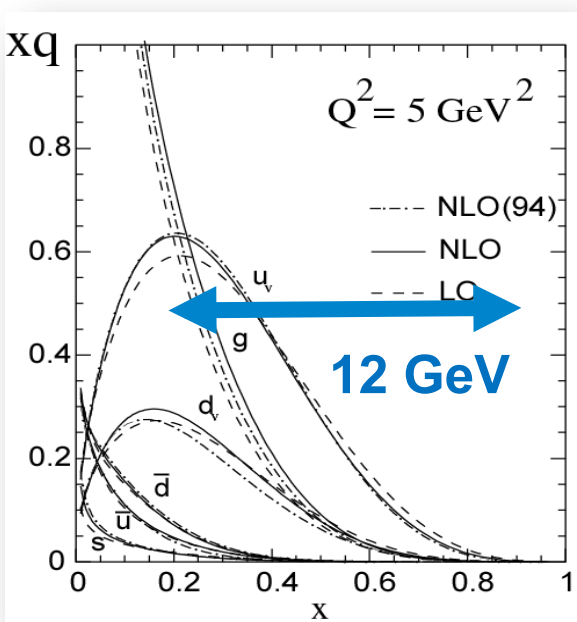
"An Electron-Ion Collider (EIC) with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia."

→ EIC collaboration, involves both BNL and JLab communities

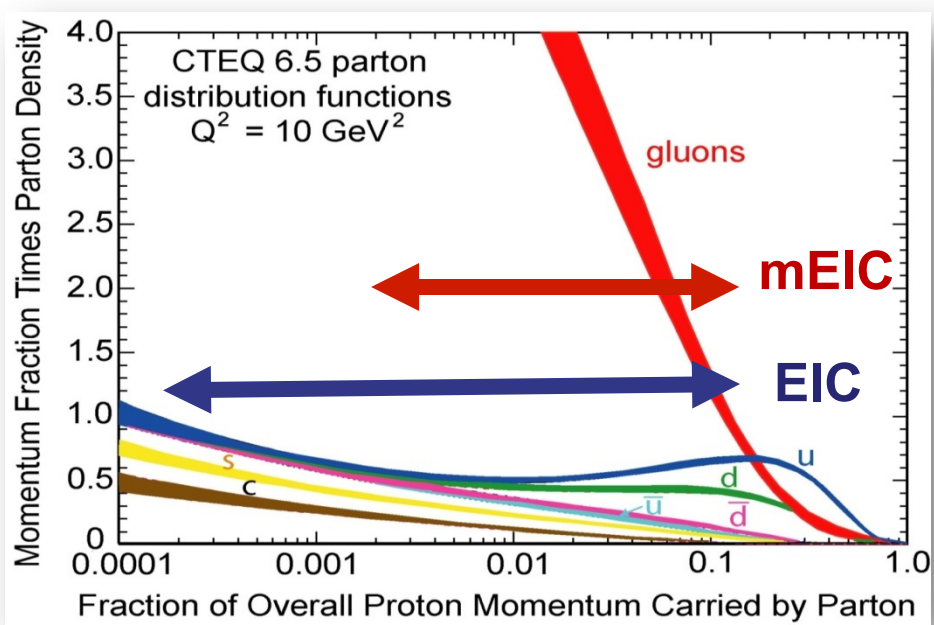
→ JLab and BNL developing "staged" designs

→ EIC Advisory C'tee: Montgomery & Aronson

With 12 GeV we study mostly the *valence quark* component

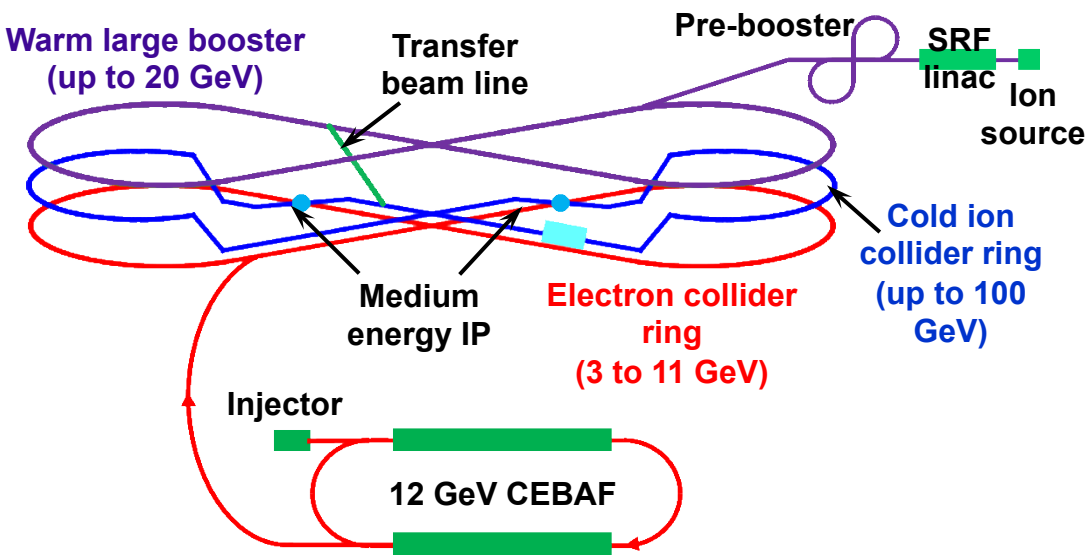


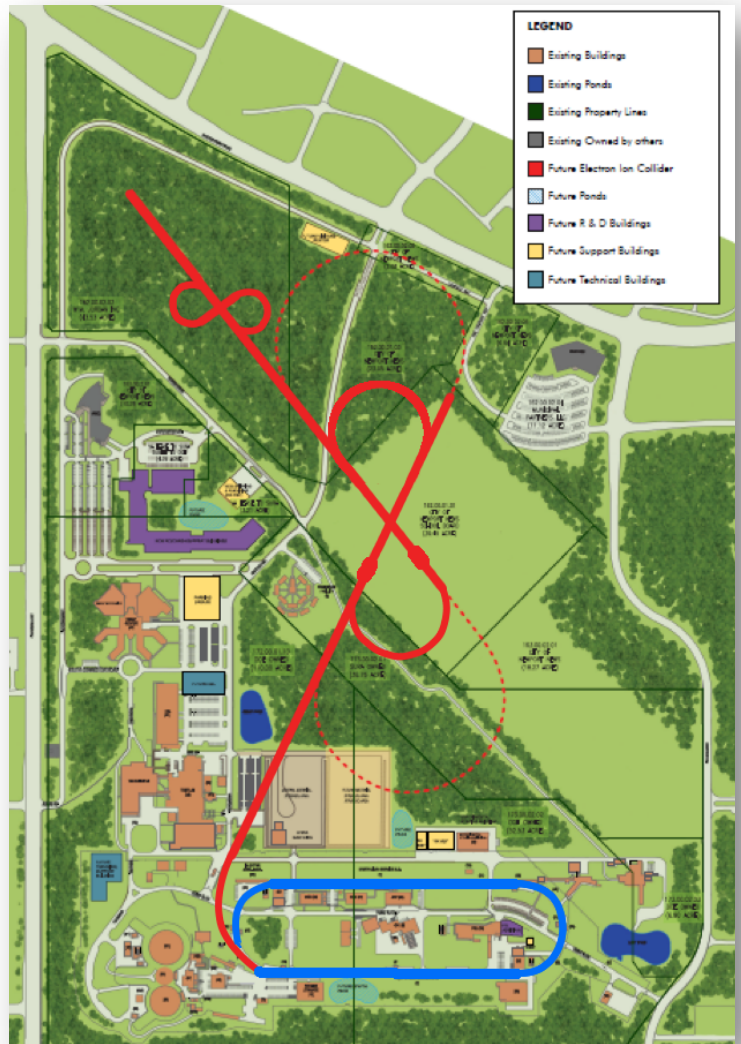
A polarized EIC aims to study *gluon* dominated matter



Electron Ion Collider

MEIC Medium Energy EIC



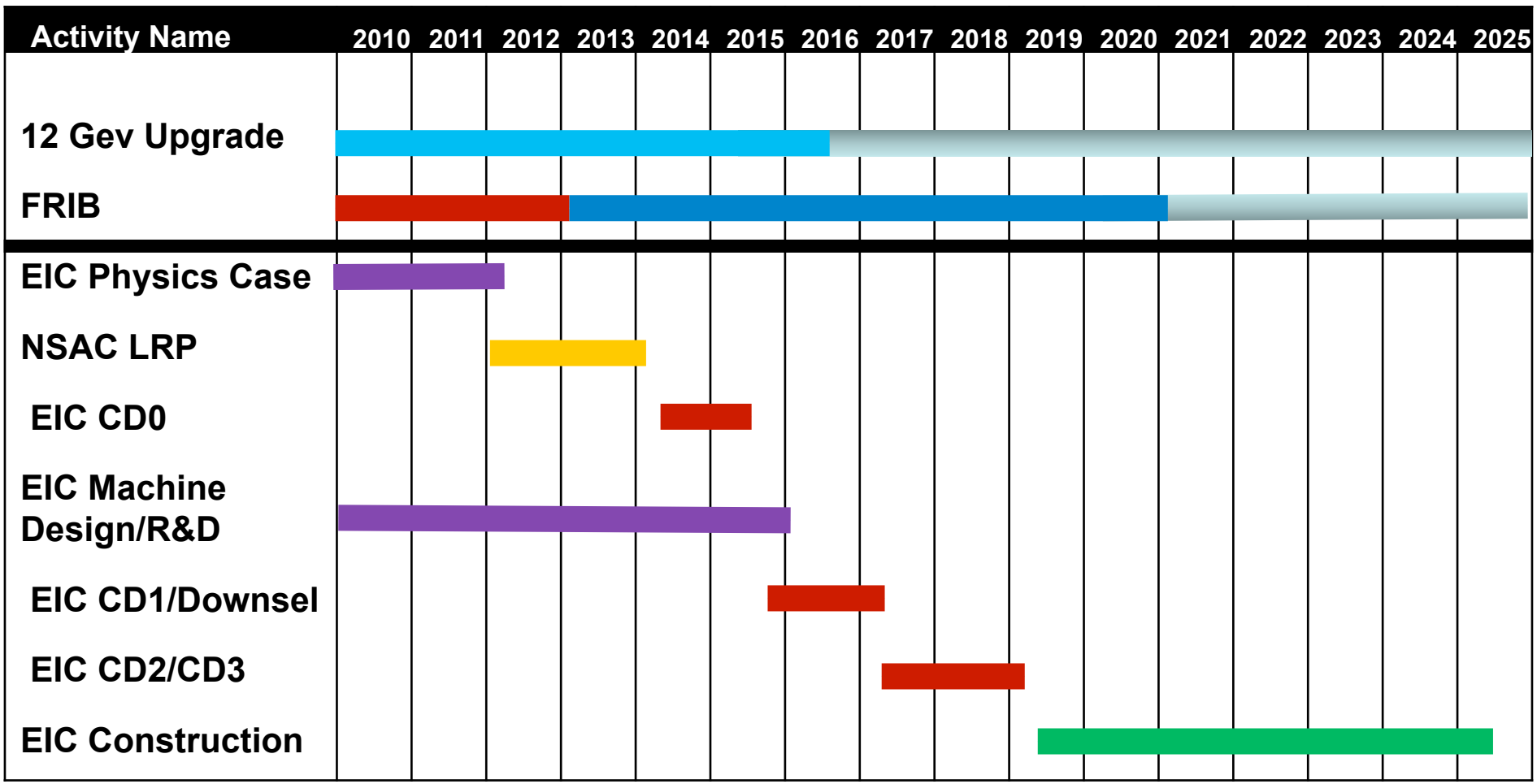


Jefferson Lab Concept

- **Initial configuration (MEIC):**
  - 3-11 GeV on 20-100 GeV ep/eA collider
  - longitudinal and transverse polarization
  - high luminosity (up to few x 10^{34} e-nucleons cm^{-2} s^{-1})
- **Upgradable to higher energies** (250 GeV protons)

Electron Ion Collider

Timeline (as of Feb. 8, 2013)



Summary

- Eagerly awaiting 12 GeV running
  - → expected to reveal rich, multi-dimensional structure of nucleon with high precision
  - → first beam expected 2014
- Many areas of complementarity in nucleon (& nuclear) structure studies at Jefferson Lab and J-PARC
  - → similar (large-x) physics probed by different beams
  - → cannot have full understanding without input from both
- Opportunity for close cooperation between communities

ありがとうございました

to workshop organizers!